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THE EFFECT OF ACHROMATIC CONDITIONS ON THE COLOR PHENOMENA OF PERIPHERAL VISION.

BY

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THE EFFECT OF ACHROMATIC CONDITIONS ON THE COLOR PHENOMENA OF PERIPHERAL VISION.

BY GRACE MAXWELL FERNALD.

I. INTRODUCTION AND HISTORICAL SKETCH.

Introductory Statement.

The present investigation has as its purpose the determination of the effect of achromatic conditions on the color phenomena of peripheral vision.

Von Kries[1] has already shown that the Purkinje phenomenon, in so far as it consists of changes in the relative brightness of the different colors, occurs at the periphery. It has been shown by Miss Thompson and Miss Gordon,[2] as well as by the writer,[3] that the brightness of a colorless background has a decided effect on the tone of peripheral color stimuli and on the appearance and relative frequency of the after-images which follow these stimuli.

In the present investigation a part of the previous work has been repeated and verified; observations have been made under more varied brightness conditions than those employed in our previous work in order to determine (1) what effect these achromatic conditions have on the color phenomena, and (2) just what factors are responsible for the changes observed;

[1] J. von Kries, 'Ueber die Farbenblindheit der Netzhautperipherie,' *Ztsch. f. Psychol. u. Physiol. d. Sinnesorgane,* XV., 1897, S. 247–279.

[2] H. B. Thompson and K. Gordon, 'A Study of After-images on the Peripheral Retina,' Psychol. Rev., Vol. XIV., 1907, pp. 122–167.

[3] G. M. Fernald, 'The Effect of the Brightness of Background on Color in Peripheral Vision,' Psychol. Rev., Vol. XII., 1905, pp. 386–425; *ibid.,* Vol. XV., 1908, pp. 25–43.

finally, an attempt has been made to correlate the phenomena observed with the facts previously established concerning peripheral and central vision, under conditions of light and dark adaptation respectively.

I wish to express my gratitude to Professors James R. Angell and John B. Watson, of the University of Chicago, for suggestions and assistance throughout the entire investigation. I am also greatly indebted to the observers, instructors and students at the University of Chicago and at Bryn Mawr College, for the time they so generously gave to the work.

Historical Statement.

A. *Methods of Investigation.*

Any historical account of the work on peripheral color vision presents a series of seemingly irreconcilable statements. A study of the methods employed in the various investigations serves, however, to explain why such a state of affairs should exist.

As Baird[4] has given an exceedingly accurate and complete history of the experimental work up to the spring of 1905, it will only be necessary here to state the actual differences in methods which may affect the outcome of the investigations, and to give a somewhat detailed description of some of the more recent papers which have direct bearing upon the special problem to be discussed in this monograph. A brief section is also given on the effect of brightness adaptation.

1. Apparatus.

The perimeter has been employed in all the more important investigations of the dark-adapted peripheral retina, as well as in some of the earlier investigations of light-adapted vision. With this apparatus the eye fixation remains constant, while a small sector of the stimulus color is moved in or out along the quadrant of the perimeter arc. The advantage of this method is that the eye takes a fixation straight ahead and does not have to turn to the side when the peripheral retina is stimulated.

[4] J. W. Baird, 'The Color Sensitivity of the Peripheral Retina,' Carnegie Institution of Washington, May, 1905, pp. 80.

In daylight illumination, however, there is a change in the brightness of the color at different points on the arc, unless all the illumination comes from a skylight.

The campimeter has been used in many of the investigations in daylight illumination. The advantage of this apparatus is that it makes possible a more extended background than could be employed with the perimeter and an easier control of the brightness of the stimulus in daylight.

Among the more recent investigators, Hess and Kirschmann used the campimeter in daylight illumination, while Hellpach and Baird used the perimeter in the dark room.

2. Methods of Observation and Stimulation.

(a) *Moving and Stationary Retinal Image.*

Either the eye or the stimulus was moved during stimulation in all the determinations of the color limits up to the time of Hellpach's work in 1900. In the investigations with the perimeter the eye remained stationary while the stimulus was moved in from the periphery to the center of the visual field, or vice versa; while in the work with the campimeter the eye followed a moving fixation point and the stimulus was stationary. An exception to this latter statement occurs in the case of Kirschmann's work on the campimeter. He maintained a stationary fixation and moved the stimulus, thus constantly changing the size of the retinal image. Hess also varied the method slightly by covering and uncovering the stimulus while the eye followed a moving pointer.

In any case the constant movement of the retinal image would be open to the following objections: (1) The observation would be difficult owing to the constant shift of the image; (2) the portion of the retina stimulated at a given moment would not be entirely unfatigued; (3) the constant movement of the image would make it very difficult to record exactly the points at which the various phenomena occur.

In the work with the campimeter, eye movement during stimulation introduces still further difficulties, as it is now well established that eye movement is necessarily irregular and also that vision is influenced by eye movement.

A further reason for employing a stationary fixation and a stationary stimulus is that this is the only method which is adapted for the observation of after-images, either in peripheral or central vision.

In the investigations of the peripheral retina, Hellpach and Baird used the method which was also adopted throughout our work, namely, that of stationary fixation and stimulus, with an interval of two or more minutes between stimulations.

(*b*) *Interval Between Stimuli.*

If the method of stationary fixation and of stationary stimulus is employed, the question at once arises as to the length of the interval which should intervene between stimulations. Hellpach allowed a three-minute interval. Baird claims that three minutes is not long enough to overcome fatigue effects and consequently he allowed a six-minute interval.[5] Miss Thompson and Miss Gordon allowed a two-minute interval in the first half of their work and a five-minute interval in the remainder. They found no difference whatever in the results in the two cases. In all our work only a two-minute interval has been allowed. The reasons why a longer interval seemed unnecessary have been given in a previous paper.[6] They are briefly as follows:

1. Though gray, white and black stimuli were frequently used, they always appeared colorless.

2. The stimulus was never seen as the color complementary to the previous stimulus, but always gave a perfectly characteristic response.

3. The after-images when experienced were the characteristic after-images of the immediate stimulus and not of previous stimuli.

4. As shown by the work of Miss Thompson and Miss Gordon, the results were in no wise altered by increasing the length of the interval.

[5] Baird found that, when stimuli are given in too close succession, a stimulus sometimes appears as the color complementary to the previous stimulus (*cit.*, pp. 57–58).

[6] *Journal of Philos., Psychol. and Sci. Method,* Vol. III., pp. 352–353.

(*c*) *Retinal Area of Stimulus.*

Several attempts have been made to determine the effect produced by a change in the size of the retinal image. There is a decided disagreement in the conclusions reached as a result of these investigations. The experiments of Woinow[7] and Krükow[8] show no change whatever in the limits of the retinal fields due to change in the size of the stimulus. Kirschmann[9] found the limits for all the colors greatly widened on the upper and nasal half-meridians, but little changed on the lower and temporal, as the size of the retinal image was increased. All the other investigators who have worked on this problem agree that increase in the size of the retinal image results in a widening of the limits for all the colors.

It is quite possible that the lack of agreement may be due to the different amounts by which the stimuli were decreased as well as to the difference in the size of the original stimulus. It seems probable that, starting with a minimum visible stimulus and gradually increasing the size of the stimulus as much as is practicable, different phenomena would accompany various degrees of change. It is also true that in most cases, there is no way of determining the relative brightnesses and saturations of the stimuli used by different investigators, so that either or both of these factors may be at least partly responsible for the lack of uniformity in the results.

(*d*) *Urfarben as Stimuli.*

Bull[10] (1881) found that there are only four colors which do not change in tone as they are moved from the center to the periphery of the visual field. These colors are a blue-green, a purple, a yellow and a blue. The colors were equated in saturation by using such proportions of the complementary Urfarben that 180° of one cancelled 180° of the other. This

[7] M. Woinow, 'Zur Farbenempfindung,' *Von Graefe's Archiv*, XVI., 1, 1870, S. 212–224.

[8] Krükow, 'Objective Farbenempfindungen auf den peripherischen Theilen der Netzhaut,' *Von Graefe's Archiv*, XX., 1, 1874, S. 255–296.

[9] A. Kirschmann, 'Die Farbenempfindung in indirectem Sehen,' *Philos. Stud.*, VIII., 1893, S. 592–614.

[10] Bull, 'Studien über Licht- und Farbensinn,' *Von Graefe's Archiv*, XXVII., 1, 1881, S. 54–154. Sur la périmètrie au moyen de pigment colorés. *Annales d'Oculistique*, CX., 1893, pp. 169–181.

method serves simply to equate the red with its complementary green and the yellow with its complementary blue. Unfortunately there seems to be no way of equating the saturation of the blue and the yellow with that of the red and the green. Bull found the limits for green and red practically coincident. The fields for blue and yellow were practically equal in extent, the field for blue being somewhat wider than that for yellow, and were in every case considerably wider than the fields for green and red.

Hess[11] (1889) determined the color limits for the Urfarben, after the complementary Urfarben had been equated with each other in saturation and all the colors had been matched in brightness to a neutral gray screen. He found the limits for the Urroth equal to those for the Urgrün and the limits for the Urblau equal to those for the Urgelb. The limits for the latter pair of colors were wider than those for the former pair.

Hegg[12] repeated and confirmed the work of Bull and Hess. The greater part of all three investigations was made with pigment colors in daylight illumination.

The only determination of the limits of the stable colors with the dark adapted retina is that made by Baird and reported in the monograph already referred to.[13] For stimuli he used light transmitted through gelatin filters. The complementary Urfarben were equated in saturation and all four Urfarben were equated with each other in brightness. The coincidence of the fields of the two pairs of stable colors, already established in the case of light-adapted vision, was found to exist also in dark-adapted vision. Unfortunately there seems to be no way of determining whether the tone of the color which was the Urfarbe in light-adapted vision was the same as that of the Urfarbe in dark-adapted vision, nor whether, as has already beeen suggested, the blue and the yellow equalled the red and the green in saturation.

[11] Hess, C., 'Ueber den Farbensinn bei indirectem Sehen,' *Von Graefe's Archiv*, XXXV., 4, 1889, S. 1–62. (Also *Annales d'Ocul.*, CX., p. 177.)

[12] Hegg, Emil, 'Zur Farbenperimetrie,' *Von Graefe's Archiv*, XXXVIII., 3, 1892, S. 145–168; 'La périmètrie des couleurs,' *Annales d'Oculistique*, CIX., 3, 1893, pp. 321–347; 'Sur la périmètrie au moyen des pigments colorés,' *Annales d'Ocul.*, CXI., 1894, pp. 122–127.

[13] Baird, Carnegie Monograph, 1905.

It seems to be established, however, beyond question that, under fixed conditions of illumination, there are four and only four colors which do not change as they are moved from the center of the field of vision to the periphery, and that when the Urroth and Urgrün and the Urblau and Urgelb, respectively, are equal in saturation and brightness, the fields for the Urroth and Urgrün and for the Urblau and Urgelb, respectively, are equal in extent.

(*e*) *Brightness of Background.*

In the work carried out in daylight illumination there has been as great a diversity in the backgrounds upon which the stimulus has been exposed as in the various other conditions. Very little work has been done for the express purpose of determining what influence the background exerts on the extent of the color fields and on the character of the color perceived.

Aubert used both black and white backgrounds and found that all the colors were perceived further out on the black background than on the white background.

Woinow and Krükow insist that change in the brightness of the background, like change in other conditions, has no effect on the distribution and size of the color fields.

Hess carried out some experiments with backgrounds of different degrees of brightness. He states that the widest fields were obtained when the color and background were of equal brightness but does not give in detail the data upon which his conclusion is based.

During the years 1903–1905 the writer[14] attempted to determine the effect of the brightness of a colorless background on the appearance of color stimuli and on the extent of the color fields in peripheral vision. During the years 1905–1906 Miss Thompson and Miss Gordon made a special study of peripheral after-images.[15] As the method and the apparatus were practically the same in the two cases, the results of the two investigations will be summarized together. They are in brief, as follows.

[14] Psychol. Rev., Vol. XII., 1905; Vol. XV., 1908.

[15] Psychol. Rev., XIV., 1907.

α. *Effect of the Brightness of the Background on the Extent of the Color Fields.*—The limits for yellow and for carmine are much wider with the dark than with the light backgrounds. The limits for orange, and perhaps for red, are wider with the light than with the dark backgrounds. The limits for blue, for violet and for blue-green are little affected by changes in the brightness of the background.

β. *Effect of the Brightness of the Background on Colortone.*—Red, orange and yellow stimuli are seen as orange or red with the light background at the same degree of eccentricity at which they are seen as yellow with the dark background. No similar effect was observed in the case of blue, violet and carmine.

γ. *Effect of the Brightness of the Background on the After-image.*—After-images follow color stimuli in a larger percentage of cases with the light than with the dark backgrounds. With the dark background, the after-images for blue and green appear orange, and for violet greenish-yellow, at the same points at which they appear yellow with the dark background. The after-image for red, orange and yellow is blue with both the light and the dark backgrounds.

(*f*) *Intensity of Stimulus and Brightness Adaptation.*

There is a general agreement that increase in the intensity of a stimulus extends the limits of sensitivity of a color. Baird concludes on the basis of his own experimentation that sufficiently intense stimuli would probably be seen at the extreme periphery.

Another effect produced by changes in the intensity of the stimulus, is that described in the literature as the Purkinje phenomenon. The discussion of this phenomenon is taken up in the following section on brightness adaptation. It is evident that intensity of stimulus and brightness adaptation cannot be entirely separated, since the intensity and character of the stimulus determine the adaptation of the part of the retina stimulated.

B. *General Discussion of Brightness Adaptation in Central and Peripheral Vision.*

The effect of brightness adaptation on the various spectral colors has been more fully worked out for central vision than for peripheral vision. The general name applied to the changes which occur is the Purkinje phenomenon, inasmuch as the first mention of them was made by him (1825).[16] In his Neue Beiträge the following description occurs: "Objectiv hat der Grad der Beleuchtung grossen Einfluss auf die Intensität der Farbenqualität. Um sich davon recht lebendig zu überzeugen, nehme man vor Anbruch des Tages, wo es eben schwach zu dämmern beginnt, die Farben vor sich. Anfangs sieht man nur schwarz und grau. Gerade die lebhaftesten Farben, das Roth und das Grün, erscheinen am schwärzesten. Das Gelb kann man von Rosenroth lange nicht Unterscheiden. Das Blau war mir zuerst bemerkbar. Die rothen Nüancen, die sonst beim Tageslichte am hellsten brennen, nämlich carmen, zinnobar und orange zeigen sich lange am dunkelsten, durchaus nicht in Verhältnisse ihrer mittleren Helligkeit. Das Grün erscheint mehr bläulich, und seine gelbe Tinte entwickelt sich erst mit zunehmenden Tage."

Since this observation was made by Purkinje, the changes connected with varying degrees of light and dark adaptation have been made the object of extended investigations. Two methods of changing the brightness adaptation have been employed, (1) local and (2) general; *i. e.,* (1) the intensity of the colors observed may be varied with a minimum change in general brightness conditions, as for instance when a spectrum observed in a dark room is varied in intensity; or (2) the intensity of the stimulus may be varied by a change in general illumination,—when the illumination of a room is increased or decreased. In the former case it is necessary to suppose that the greater part of the retina remains practically dark-adapted, and that any change in the relative brightness and saturation of the colors is due to local adaptation. In the latter case, in which changes in the intensity of the stimulus are due simply to

[16] J. Purkinje, 'Beobachtungen und Versuche zur Physiologie der Sinne,' Band II., 'Neue Beiträge zur Kenntniss des Sehens in Subjectiven Hinsicht,' 1825, p. 109.

the greater or less amount of light reflected from the colored surface, adaptation changes, similar to those which are found in the region of direct stimulation, must also occur over the entire retinal field. The results obtained under both sets of conditions agree in so far as they are concerned with the relative brightness and saturation of the spectral colors.

A spectrum of minimum intensity appears as a series of brightness bands, with the brightest section in the region of green (provided the eye is thoroughly dark-adapted), and the darkest in the region of yellow and red. As the intensity of the spectrum is increased the maximum brightness shifts from green to blue and finally, when still greater increase is made in intensity, to yellow—the appearance of the spectrum in ordinary illumination and brightness. The same general shift of brightness values occurs with pigment colors observed in a very faint illumination which is gradually increased to full daylight. The observation quoted from Purkinje (see p. 9) evidently describes the intermediate stage in which blue is the brightest color.

The order in which the colors are distinguished as the general illumination or the intensity of the spectrum is increased, does not correspond with the brightness shift. If the brightness of a spectrum of medium intensity is slowly decreased, red, blue and green gradually spread over the entire spectrum until they are the only colors visible. The red end is, in this case, the darkest part of the spectrum, the blue the brightest. As intensity is still further decreased, the green and then the blue fade out to gray leaving red as the last color visible.[17]

[17] Accounts seem to differ somewhat concerning the exact order in which the various colors disappear as the intensity of the spectrum is decreased. The statement given above is taken from Ebbinghaus—'Theorie des Farbensehens,' *Ztsch. f. Psychol.*, Bd. V., 1893, S. 155. Helmholtz agrees with Ebbinghaus in giving red as the last color visible in a spectrum of decreasing intensity—Helmholtz, 'Physiol. Optik,' Aufl. II., p. 471. Mrs. Ladd-Franklin gives green and red as the last colors visible—Baldwin's 'Dict. of Philos. and Psychol.,' Vol. II., p. 796. W. von Bezold and E. Brücke first observed that yellow and cyan blue lose their color before red, green and violet-blue (cf. Helmholtz, 'Optik,' S. 469). Wundt states that blue and violet are the first colors distinguished in a spectrum of gradually increasing intensity, and the last to be lost under the reverse conditions. (Wundt, 'Physiol. Psychol.,' Aufl. V., Bd. II., S. 173.) For Purkinje's statement see p. 9 this monograph. All the above agree that yellow is one of the first

No especial stress is laid on any changes in color-tone which accompany the changes in brightness. Several writers, however, mention the fact that certain changes occur. Thus Purkinje states that green appears more bluish and consequently less yellow in faint illumination, and that, under similar conditions, yellow cannot be distinguished from rose-red. Ebbinghaus[18] is undoubtedly describing a similar phenomenon when he speaks of the red, blue and green as spreading over adjacent colors in a spectrum of faint intensity. It is probable that the changes which accompany the darkening of pigment stimuli are analogous phenomena. For example, a red stimulus becomes deeper and more saturated and an orange stimulus becomes redder when darkened.

Undoubtedly the work done in the dark room, with spectral lights as stimuli, has been performed under more accurately controlled conditions, than when daylight is depended on for illumination. The changes, however, in relative brightness and saturation of the different parts of the spectrum are so pronounced that they can be illustrated very easily in a roughly conducted experiment in increasing or decreasing daylight illumination. Moreover, the experiments in daylight, despite any necessary irregularities in experimental conditions, deal with problems which cannot be investigated in any other way—namely, those presented by the phenomena of light-adapted vision.

Most of the investigations in peripheral vision with stimuli of different intensities, have been carried out in the dark room with self-luminous stimuli. Few of these have used stimuli differing sufficiently in intensity to determine whether the Purkinje phenomenon occurs at the periphery or not. Von Kries, working with self-luminous stimuli in the dark room, has shown that the Purkinje phenomenon, in so far as it consists of changes in the relative brightness of colors, exists at the extreme periphery beyond the limits for color vision: *i. e.,* if a red and a green appeared as matched grays at the periphery, the red

colors to disappear as the intensity of a spectrum is gradually decreased, and all but Wundt and Purkinje agree that red is the last or one of the last to lose its color component under the same conditions.

[18] *Cit.,* p. 155.

became much darker than the green when the intensity of both colors had been equally decreased by a certain amount.

The explanation most generally accepted, for at least a part of the phenomena just described, is that the development of the visual purple or 'rod pigment' during dark adaptation in some way heightens the brightness effect of certain colors, so that these colors appear relatively brighter than colors not thus reinforced.

Mrs. Ladd-Franklin and Von Kries hold that the effect of the rod pigment is due to its power to absorb certain colors and so intensify their brightness. In this case the brightness alone would be affected, because the rod pigment exists only in the rods which are the organs for colorless vision. According to this theory, the visual purple, in its completely bleached-out state (*i. e.,* in full illumination), has no effect whatever on brightness values. In an intermediate state of partial dark-adaptation, when the rod pigment can best be described as the visual yellow, it absorbs the blue light, so intensifying its effect on the rods and causing it to appear relatively brighter than the other colors. In its final stage of dark adaptation, the rod pigment becomes purple (hence the name 'visual purple') and absorbs green light, so intensifying the brightness of green.

Mrs. Ladd-Franklin explains the fact that blue and green, though relatively brighter than red, lose their color component at a higher intensity of stimulus than does red, by the overlaying 'of the color by the white constituent furnished by the rods.' Her statement is as follows:[19]

"In proportion as the blues become relatively brighter, they become also less saturated, and still more the greens as they become bright, become finally wholly uncolored. The reinforcement occurs, that is to say, not for the color in itself, but only by way of mixing in more white or gray. (This is sufficient doubtless, to account for the fact that in a very faint spectrum blue is not seen at all: The spectrum looks simply red or green, and this in spite of the fact that the Purkinje phenomenon is usually supposed to consist exactly in the brightening of this color. The blue becomes, in fact, so much overlaid

[19] C. Ladd-Franklin, Baldwin: 'Dict. of Philos. and Psychol.,' Vol. II., p. 796.

with the white constituent furnished by the rods that it is no longer visible as blue.)"

The main reasons advanced for adopting this explanation for the Purkinje phenomenon are as follows: (1) The absorption spectrum of the visual purple, when extracted from the eye, has the same brightness distribution as the spectrum of the normal dark-adapted eye; (2) the visual purple is found only in the rods, which are supposed to be the brightness sensing end-apparatus (the purple would intensify the brightness effect of the colors which it absorbs); and (3) the Purkinje phenomenon is absent at the fovea which contains cones but no rods and consequently no visual purple. (For other reasons as well as differences in theory see articles of Mrs. Ladd-Franklin and Von Kries, referred to in the bibliography, p. 88.)

The changes in color-tone which accompany variations in brightness and saturation have not, so far as we are aware, been discussed in connection with any of these explanations. Mrs. Ladd-Franklin's statement as just quoted does not seem to offer a satisfactory explanation for the fact that an orange loses its yellow constituent and appears pure red when its intensity is sufficiently decreased, since the red and the yellow would have to be equally overlaid by the brightness constituent furnished by the rods and so would have their saturation equally affected by the decreasing intensity of the stimulus.

In the present writer's opinion Mrs. Ladd-Franklin's theory does not seem competent to offer a satisfactory account of the changes in the relative saturation of colors, or of the changes in the color tone of certain colors (see pp. 72ff.). In this respect, however, it does not differ from other color theories.

C. *General Summary.*

The extent of the color fields is influenced by various factors, such as the size of the retinal image, the intensity of the stimulus, the brightness of the background, and, in all probability, by the state of light or dark adaptation of the retina. The quality of the color stimuli seems also to be affected by changes in these factors, with the possible exception of the first, *i. e.*, the size of the retinal image.

The peripheral portions of the retina are less sensitive to colors than the central and paracentral regions. In general and under such conditions as have thus far been employed, all colors appear as blue or yellow or as colorless at the periphery, though red and possibly green may be perceived at a greater degree of eccentricity on a light than on a dark background.

After-images generally follow peripheral color stimuli in light-adapted vision, but are practically absent in dark-adapted vision. The color-tone of the after-image, in the former case, is influenced by the brightness of the background, the after-images for green and blue tending to appear more reddish and for carmine and violet more greenish with the dark than with the light background.

In addition to the points more explicitly mentioned in the preceding pages, it may be noticed that adaptation to colors (*i. e.*, such that the colors fade into gray) takes place more rapidly at the periphery than at the center of vision.[20] With the dark backgrounds or under conditions of dark adaptation, the colors, with the exception of the Urfarben (see p. 5), go through a series of changes in tone before they fade out to gray, the change being in all cases toward blue or yellow. With the light background no such change in color tone occurs, but the color fades directly into gray.

Under fixed conditions of illumination there are four and only four colors which do not undergo any change in color-tone as they are moved from the center to the periphery of the field of view. These are: (1) Purplish red, and (2) its complementary color, blue-green, (3) blue and (4) its complementary yellow. When the two pairs of complementary Urfarben have been equated in saturation and all four colors have been equated in brightness, the fields for blue and yellow coincide as do also the fields for red and green. The former pair of colors seem to have the wider limits, though up to the present time no method has been devised which gives any assurance that all four colors have been equated in saturation.

The Purkinje phenomenon, in so far as it consists in changes in the relative brightness of certain colors, occurs at the extreme periphery.

[20] Cf. Baird, *loc. cit.*, pp. 56 and 72; G. M. Fernald, PSYCHOL. REV., Vol. XII., pp. 395, 397.

II. EXPERIMENTAL INVESTIGATION.

Formulation of Problem and Description of Observers.

The purpose of the present investigation was to determine the effect of general and local brightness conditions on the color phenomena of peripheral vision. The work may be divided into two main sections: (1) that in which fully saturated Hering colored papers were used as stimuli and (2) that in which the stimuli consisted of 'Urfarben' built up by appropriate mixtures of Hering discs. Both series of stimuli were tested under varying brightness conditions.

Nine observers, all possessing normal vision, served as reagents in the present investigation. Of these Dr. Harvey Carr (C), Dr. Joseph Peterson (P), Dr. Clarence Yoakum (Y), and the writer (F), had completed two or more years of graduate work in psychology and were familiar with the generally accepted statements with reference to color theory, P, Y, and F had at least two months' practice in the experiment before the series reported in this paper were begun. C had previously observed in an investigation involving considerable practice in holding a fixation and in the observation of color phenomena. Mr. Pritcher (Pr), instructor in mathematics at the University of Kansas, Miss Raichelen (R) and Miss Andersen (A), both undergraduates at the University of Chicago, had never done any work in experimental psychology and were not familiar with the general facts of color vision. Mr. Suiter (S) had had the first year's work in experimental psychology and knew enough about color vision to be greatly disturbed by his own results. Miss Hewett (H), a graduate student at Bryn Mawr, served as observer in the results reported from the Bryn Mawr Laboratory. She had completed one year's work in experimental psychology but had never done any special work in vision.

It seemed wise that half of our observers should be entirely unsophisticated with reference to color work, although our

method of procedure seemed to rule out any possibility of error due to suggestion. It was considered absolutely essential to carry out the entire series with well-trained observers because of the greater reliability of their observations. A study of the results shows throughout a striking agreement between those obtained with the two classes of observers.

Apparatus.

The apparatus consisted of a vertical campimeter exactly like that used in the second part of our previous work.[1] The frame of the campimeter was supported by iron clamps, so constructed that they fitted exactly over iron bars which were screwed to a heavy, solid table.

"The campimeter frame *IJKL* (see Fig. 1) was fastened to heavy iron bars *AB* and *CD*, which were placed, parallel to

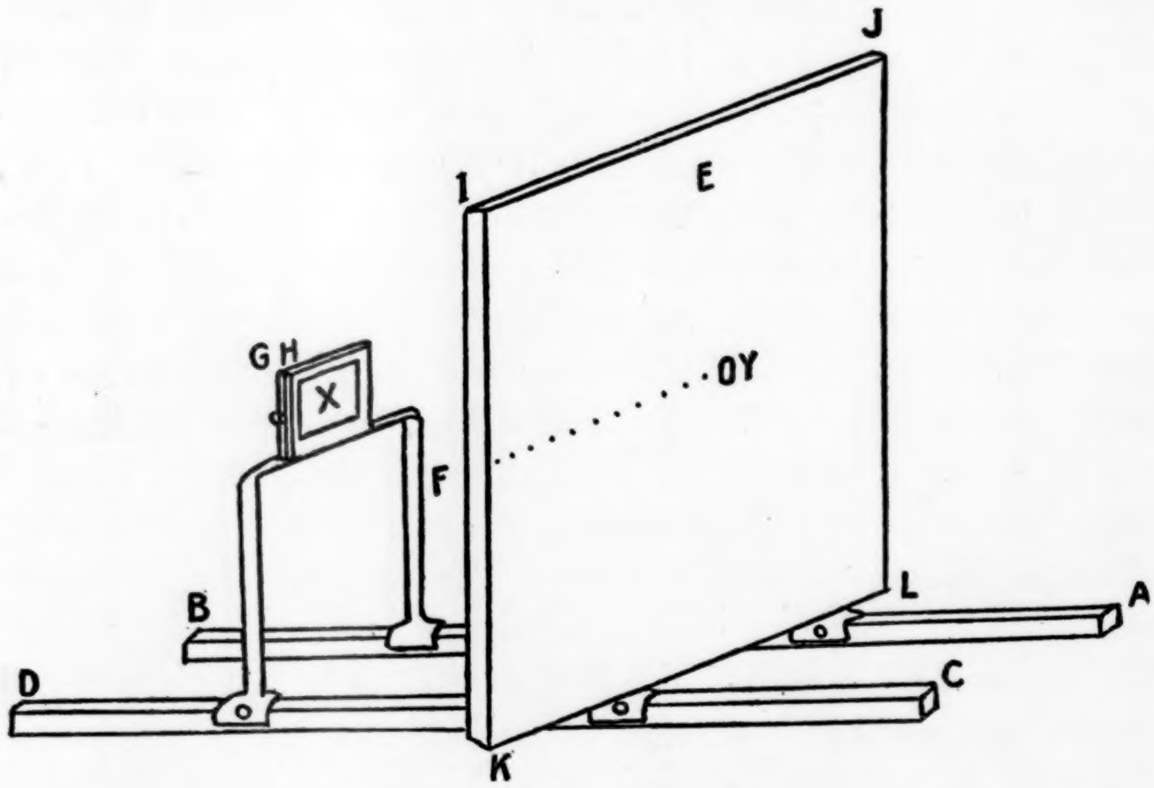

Fig. 1.

each other, on a long table. Behind the frame *IJKL* was an iron support *F*, which was also secured to the iron bars *AB* and *CD*. This support carried a frame, furnished with two

[1] Psychol. Rev., Vol. XV., 1908, p. 27.

grooves, *G* and *H*, into which small frames could be slid. A gray slide (*x* in the diagram), like the background in brightness, was fitted into the first of the two frames, *i. e.*, the one toward the campimeter, and the stimulus color into the second. . . . As the limits for the nasal meridian could not be obtained on the flat surface of the campimeter, a second frame was attached to the main campimeter frame, perpendicular to the surface of the campimeter along the edge *IK*."

An electric color mixer was suspended just behind the slide so that various color mixtures could be used as stimuli in place of the color slides. The entire apparatus was constructed with especial reference to solidity, as it was essential that there should be no change in the relations of the parts to each other, and to the source of illumination after the adjustments had once been made.

The backgrounds as well as the screens used to cover the stimulus when it was not exposed, were made of platinum paper or of the dead white and black of the Hering color series (*i. e.*, not numbers 1 and 50 of the Hering gray series). The platinum backgrounds were finally obtained after six months of strenuous effort. It was exceedingly difficult to get large enough sheets of paper printed evenly and toned to exactly the desired shade of gray, but the grays finally secured were far superior to any wash papers on the market. It might be stated here that the Hering grays used in our earlier work were very unsatisfactory because of their evident blue tone. Platinum was chosen in preference to any other photographic paper, because it has the dullest finish of any of those which print a pure gray. The paper was stretched on a canvas-covered frame, which was screwed to the upright campimeter frame.

A circular opening (*Y* in Fig. 1, p. 16) was made in the center of the background by means of a sharp metal punch, which cut a perfectly even line, and yet bent the edges of the paper back so that there was no white ring about the opening. Two sizes of opening were used, the larger being 12 mm. in diameter, the smaller 5 mm. Fixation points measuring degrees, calculated on a basis of an arc of 25 cm. radius, were marked out on the background, starting with the center of the opening *Y* as zero.

A circle was made on the gray slide, which concealed the stimulus color (X in Fig. 1); its size being such that when the eye was 25 cm. from the campimeter opening, the circle on the slide seemed to fit just inside the circle of the campimeter opening.[2] The center of the former circle was determined by placing a ruler perpendicular to the campimeter at the center of the opening. This method of determining the relative positions of the two circles was not so exact as the cathetometer method used in our earlier work, but the dimensions of the room made this latter method impracticable in the present case. No serious error could have been introduced by this change of method since the relative positions of the two circles were kept constant throughout the experiment.

The head was held in position during stimulation by means of a black sealing-wax mouthpiece in which a deep indentation of the observer's teeth had been made. It is evident that, when the apparatus had once been adjusted, the head position was absolutely determined, provided the mouthpiece was secure. To insure the stability of the mouthpiece, it was fastened to a triangular support which was screwed to the table.[3]

The work was all carried on in a north room which had been especially provided with a 4½ by 5½ ft. plate glass window, so that there was an abundance of north light, and an exceedingly constant illumination. The walls and woodwork of the room were calcimined a medium light gray and the floor was painted the same shade. The work was all done on bright days between the hours of nine A.M. and three P.M. As far as possible the results for a given observer were obtained at the same hour on successive days.

[2] Data (after Howell) for determining the diameter of the retinal image: Eye to stimulus, 25 cm.; retina to nodal point, 15.5 mm.; surface of cornea to nodal point, 7.3 mm.; diameter of stimuli 12 mm., 5 mm.

$$12 : x :: 250 + 7.3 : 15.5.$$
$$x = .7 \text{ mm.} +$$
$$5 : x :: 250 + 7.3 : 15.5$$
$$x = .3 \text{ mm.} +$$

[3] Psychol. Rev., Vol. XV., p. 27–28.

Method of Procedure.

The observer was seated in front of the campimeter so that his right eye was on a level with the opening. The mouthpiece was so adjusted that, when he fixed his teeth in it, his eye was brought into such a position that the circle on the screen appeared to fit exactly into the circle of the campimeter opening. There is only one eye position in which the two circles seem concentric, *i. e.,* the one in which the visual axis coincides with the line through the centers of the campimeter opening and of the circle (x) on the screen.

After the eye position had been determined according to the method described, the observer took a given fixation point, while the experimenter, after a 'ready' signal, removed the screen, thus exposing the color. The observer started a stop-watch as soon as he saw the stimulus (*i. e.,* recognized it either as color or brightness) and stopped it as soon as all color disappeared. The second click of the watch served as a sign to the experimenter to push the screen back over the color. At the less eccentric fixation points the time of stimulation was arbitrarily limited to four or five seconds. The observer held the fixation until all trace of the after-image had disappeared. A two-minute interval was allowed between stimuli. The interval began when the after-image had completely disappeared. All the results were obtained on the nasal half-meridian.

In the first part of the work the stimuli consisted of colored slides, made of Hering colors (new series). The colors used were red, orange, orange-yellow, yellow-green, green, green-blue, violet and carmine. The stimuli were given on the different backgrounds (*i. e.,* platinum white, middle gray and black, Hering black and white and later Hering green, see p. 45) at degrees of eccentricity between 20 and 90 degrees. The stimuli were given in no regular order, so that the observer had no clue whatever as to the color used. To still further guard against the effects of suggestion, black, white and grays matching the various colors in brightness were frequently employed as stimuli. The observer was never given any information concerning the actual color or brightness stimuli used, but was shown samples of all the colors of the Hering series and asked

to identify the color he had seen with a color in the series—or, if an exact identification of the colors was not possible, to locate the color observed between any two colors of the series.[4] After the effect of the background on these colors had been determined, the same stimuli were observed under different sets of general and local brightness conditions.

In the second part of the work the electric color-mixer was used. The four stable colors, made up of mixtures of the Hering colors used in Section A, were first determined on the middle gray background, and then tested with the black and the white background. They were then equated in brightness and saturation according to the method employed by Hess (see p. 62), and tested for their limits on the different backgrounds.

Results.

Section A. Observations made with Hering Colored Papers as Stimuli.

1. *Effect on the Stimulus of Changes in Brightness Produced* (*a*) BY CHANGES IN BRIGHTNESS OF BACKGROUND AFFECTING

(α) *Variations in Color Tone of Stimulus.*—We may mention first the appearance of the stimuli with the white background. Yellow, orange and red, or the colors at the red end of the spectrum, are the only ones which undergo distinct qualitative change, due to the change in the brightness of the background. The effect of the background upon all these colors is, however, so great that observers suppose an entirely different series of stimuli have been used with the dark and with the light backgrounds. The results of the present investigation confirm the statement made in our previous papers, namely that the light background tends to emphasize the red component of red and orange stimuli. In the present investigation red was seen as red much farther out on the periphery than in any of our previous work and yellow was invariably seen as orange or red at the periphery. This is undoubtedly due to the fact that a white instead of a light gray background was used in the experi-

[4] For example a yellowish orange which was yellower than the orange and redder than the orange-yellow of the series, would be described as between these two latter colors.

ment here reported, and that the illumination was greater than any we had previously been able to obtain. The results for the different colors on the white background, are as follows (see Tables XX. and XXI., pp. 50ff.).

Orange and Orange-yellow.—Not only do orange and orange-yellow tend to appear as red in the 'red-green zone' but they are seen as clear, saturated red, practically to the outermost color limits. In fact they were perceived as red by all observers as far out as 85 or 90 degrees with the larger stimulus, and, with the smaller stimulus, to practically the outermost point at which the smaller blue stimulus is recognized under similar brightness conditions. Whenever the color is tabulated as red, the scarlet-red or the brickish red of the Hering series was designated as matching the color seen. No doubt whatever was expressed by the observers concerning the color seen. In most cases they were surprised at being questioned as to the possibility of the color being anything but red. C, P and S expressed considerable concern because red was seen at the extreme periphery, contrary to the statements of the color theories, and were sure their results must be due to some individual variation. The platinum gray, black and white, interposed in the series were never seen as color, with an exception in the case of observer C, who sometimes showed a tendency to see the middle gray and black as reddish, though not as a pure saturated red like that due to stimulation by orange and yellow.

Yellow.—All the observers tended to see the yellow as reddish with the light background, but in some cases this tendency was much more marked than in others. C and P perceived yellow as bright red as far out as it could be seen as color, while the other observers saw it as red, orange or in some cases only as orange-yellow or as golden yellow. It might be stated here that P and C showed the strongest tendency to see red throughout the entire investigation.

Red.—Red, with the white background, is seen only as red, appearing slightly more carmine at the outer limits than at the center.

Violet, carmine and *blue* all appear either in their true color-

tone or as blue at the periphery, while *green* appears colorless at all the more peripheral points.

With the dark background, of which mention will next be made, orange, orange-yellow and yellow all appear yellow or orange at all peripheral points (see pp. 53–55). Red is seen as yellow by all observers at 90 degrees with both the large and the small stimulus, but is seen as red, or as orange as far out as 85 degrees by observers P and C. These observers, however, described the orange and red, seen for any stimulus with the dark backgrounds, as a peculiar unfused mixture of red and yellow, a sort of red film over a bright luminous yellow, totally different from the carmine red resulting from these same stimuli with the white background. R saw red as red only to 65 degrees, and from 70 to 90 degrees as orange or yellow, with both the large and the small stimulus. Observer Y saw red as orange or orange-yellow from 60 to 90 degrees. Observer F perceived red as red out to 85 degrees when the dark background received full light from the window, but only as orange or yellow from 55 to 90 degrees when the background was shaded by the dark hood (see p. 54). The tables (pp. 53–55) show similar individual differences in the results for orange with this background. Orange-yellow was invariably seen as yellow or as orange-yellow, and yellow as yellow, with a single exception in the case of observer C whose yellows had a faint orange or golden tinge.

Violet, with the dark background, is seen as either blue or violet, and carmine as blue, violet or carmine. Blue appears either as blue or as colorless. The change in the brightness of the background seems to have very little effect on the quality of the colors perceived for these three stimuli, except in the case of carmine, which appears slightly redder with the light than with the dark background (see pp. 56–57).

(β) *Influence on the Saturation of the Color Stimuli and on their Zonal Limits of Changes in Brightness of Background.* —All the stimuli, except those which are seen as red on the light background, appear less saturated on the light than on the dark background, at all peripheral points. Of these latter stimuli, red appears rather less saturated to most observers on

the light than on the dark background, but orange, yellow-orange and yellow appear as very well saturated reds on the light backgrounds. All the observers reported them as being fully as saturated as, and in some cases more saturated than, the orange and yellow seen on the dark background.

In so far as our results justify any conclusions concerning the color limits,[5] they seem to show that all the colors except the reds are perceived at a greater degree of eccentricity with the dark than with the light backgrounds. Red is seen as red to about the same degree of eccentricity with the dark and with the light backgrounds, but is seen as yellow or orange with the dark background at the same points at which it is seen as colorless with the light background. It should be stated that the red of the series is decidedly darker than either the yellow or orange. Consequently it appeared very dark—to some observers almost blackish—on the white background. For certain observers the limits for red were widest and the color appeared most saturated on the gray background. All the results obtained with violet seem to show that, while the limits for violet as violet are little affected by the change in the brightness of the background, the stimulus is seen as blue with the dark background at the same points at which it appears as colorless with the light background. Observers P and Y failed to see blue at 90 degrees with the light background but got a well-saturated blue at the same point with the dark background. At 92.5 degrees C perceived blue as colorless with the light background and as blue with the dark background (see p. 41).

It is difficult to state the effect of brightness on orange and yellow stimuli, because of the distinct qualitative change which these colors undergo. It is, at least, possible to say that these stimuli appear as red at a greater degree of eccentricity with the light than with the dark background, and that they are seen as red or orange with the light background at the same points at which they are seen as orange or yellow with the dark backgrounds.

The general conclusions from these results would seem to be that all the colors except the reds and perhaps the greens are emphasized when brightened by contrast with a dark back-

[5] See footnote 25, pp. 65–66.

ground, but that the red appears more saturated where seen as red and is perceived as yellowish or orange, if not as red, at a greater degree of eccentricity with the dark or middle gray than with the light backgrounds.

(*b*) EFFECT ON THE STIMULI OF DECREASING THE GENERAL ILLUMINATION.

Two methods were employed for decreasing the general illumination: (1) A frame covered with a heavy black cloth (referred to throughout as the '*black hood*') was placed over the head of the observer, and (2) the entire room was darkened by hanging a black curtain over the window so that a greater or less amount of light could be admitted. The black background was used in both cases.

When the field was darkened by means of the black hood, the brightness contrast between the black background and the stimulus was heightened as the color still received full illumination from the window. Consequently the stimulus appeared very bright. Thus a double change was produced by this method, namely an increased brightness of stimulus by contrast with a dark background and a condition of partial dark adaptation. When the entire room was darkened by means of the dark curtain, the brightness of the stimulus as well as that of the general field was decreased.

(*a*) *Darkening the Field by Means of the Black Hood.* —The results obtained by this method are given in Tables XXII., XXIV., A and B, p. 54, and D, p. 56. In general they are as follows:

Darkening the Field by Placing the Black Hood over the Head of the Observer, greatly heightens the effects obtained with the dark background. The reds, oranges and yellows are seen as yellow or orange much more frequently, and much nearer the centre of vision than with the dark ground without the hood (see Tables XXIV., A and B).

In the case of observers R and F the fields for orange and orange-yellow are decidedly narrower when the black hood is used, than when the colors are seen against the black background in full illumination (see Table XXIV.), as under

the former conditions the colors appear yellower than the stimulus at the same points at which they appear as orange or orange-yellow under the latter conditions.

The field for red is decreased in extent, for observers R and F (Tables XXIV., A and B) and it is seen as yellow at points well within the limits for the color with the dark background and full illumination. The effect of darkening the field by this method is much greater with red than with orange. In some of our more recent work, Carr and Ferree reported a very peculiar appearance with the dark background and hood—namely the simultaneous perception of red and yellow. A fire red film seemed to be spread over a clear yellow. Peterson and Carr described a similar phenomenon with the dark background alone (see p. 53).

(β) *Darkening the Entire Room by Means of the Black Curtain.*—The results obtained by this method are given in the order in which they were recorded with the exception of those for observer R, which are tabulated without regard to

TABLE I.

OBSERVER R.

Black Background + Black Curtain.

Stimulus.	Color Seen.	60°	65°	70°	75°	80°	85°	90°
Yellow	Yellow			1		2'	I	I
Orange	Orange		1_b^r	(1_b)		$1^r, (1_b)$, I	II	
"	Or.-Yellow		1_b	1_b			2_b	1_b
"	Yellow			1_b	1_b	3_b	2_b2	$2, 1_b$
Red	Red					1	I	
"	Red-Or.			1_b			$3_b, 1$	
"	Orange						1	1
"	Or.-Yellow						1	2
"	Yellow							1_b

Table I. is self-explanatory except for the following points: The number of times the stimulus was seen at a given fixation point is shown by an Arabic numeral in one of the vertical columns; the Roman numerals indicate the number of times the stimulus was seen as brightness simply. Numerals in parentheses represent judgments about which the observer was doubtful. Letters used as superscripts indicate the color tone of the color seen, *e. g.*, 'r' means a reddish tone of any color seen. Letters used as subscripts indicate the color of the after-image.

The stimulus was a circle of 12 mm. diameter in every case where not stated to the contrary. In certain tests a stimulus of 5 mm. diameter was employed.

order. No attempt was made to determine anything but the general quality of the colors perceived under these conditions. The amount of illumination was varied from that obtained with one thickness of curtain to that obtained with three thicknesses. The results are given in the following tables. All results were obtained at Chicago unless otherwise designated.

Table II.

Observer S.

White Background.

Fix. Pt.	Stimulus.	Color Seen.	After-image.
90°	Or. yellow	Dk. gray	?
90°	Orange	Black	Blue
90°	Blue	Blue (?)	White (?)
85°	Blue	Black	Yellow
85°	Or. yellow	Not clear	Blue
85°	Orange	Dk. red	Blue
75°	Gray	Gray	White
90°	Blue	Black	Yellow (?)
80°	Or. yellow	Medium or.	Blue
85°	Or. yellow	Medium or.	Blue
80°	Orange	Red	Blue
75°	Or. yellow	Medium or.	Blue
85°	Orange	Orange	?
75°	Orange	Or. red	Blue
85°	Or. yellow	Dk. red	Blue
75°	Blue	Blue	Yellow
80°	Red	Black	Blue

Dark Background—Black Curtain.

Fix. Pt.	Stimulus.	Color Seen.	After-image.
90°	Or. yellow	White	Black
90°	Red	Yellow	Black
85°	Red	Yellow	Black
85°	Blue	Blue	Black
85°	Or. yellow	Yellow	Black
85°	Orange	Yellow	Black
80°	Gray	White	Black
90°	Blue	Blue (?)	Black
90°	Gray	White	Black
85°	Yellow	Yellow	Black
85°	Red	Yellow	Black
85°	White	White	Black
85°	Orange	Yellow	Black
85°	Red	Yellow	Black
85°	Or. yellow	Yellow	Black
80°	Yellow	Yellow	Black
80°	Red	Yellow	Black

The colors appeared well saturated, and were identified with the colors of the Hering series.

TABLE III.

OBSERVER H.

(Results obtained in Bryn Mawr Laboratory.)

Room Darkened by Single Curtain.

Fix. Pt.	Stimulus.	Color Seen.	After-image.
90°	Orange	Yellow	None
90°	Gray	Light	None
90°	Dk. gray	Nothing	None
85°	Orange	Yellow	None
80°	Orange	Yellow	None
80°	Yellow	Yellow	None
75°	Orange	Yel. orange	Blue
75°	Green	Light	None
70°	Orange	Yel. orange	Pale blue
70°	Gray	Light	Dark
75°	Red	Or. yellow	None
85°	Green	Light	Dark

Room Darkened by Double Curtain.

Fix. Pt.	Stimulus.	Color Seen.	After-image.
70°	Orange	Red orange	Blue
85°	Orange	Dark	None
80°	Orange	Red orange	None
80°	Gray	Nothing	None
65°	Green	Nothing	None
65°	Dk. gray	Nothing	None
65°	Orange	Red orange	Pale blue
70°	Orange	Red	Blue
75°	Yellow	Or. yellow	Pale blue
80°	Gray	Gray	None
80°	Orange	Or. red	None
80°	Yellow	Yellow	Blue
85°	Yellow	Or. yellow	Blue
75°	Orange	Red orange	Blue

TABLE IV.

OBSERVER F.

Dark Background—Single Black Curtain.

Fix. Pt.	Stimulus.	Color Seen.	After-image.
85°	Red	Faint yellow	Blue
85°	Light blue	White	None
85°	Dk. blue	Sug. of blue	None
85°	Orange	Bright yellow	Faint blue
85°	Yellow	White	?
80°	Orange	Yellow	Blue
80°	Blue	Blue	None
85°	Orange	Yellow	Blue

TABLE V.

OBSERVER F.

(Results obtained in the Bryn Mawr Laboratory.)

Black Background—Single Curtain.

Fix. Pt.	Stimulus.	Color Seen.	After-image.
85°	Orange	Or. yellow	None
85°	Red	Gray	None
85°	Red	Light	Dark
80°	Orange	Lemon yellow	None
85°	Yellow	White	None
85°	Orange	Yel. orange	None
85°	Blue	Blue	None
85°	Red	?	None
80°	Yellow	White	Blue
80°	Blue	Blue	None
80°			

Black Background—Double Curtain.

Fix. Pt.	Stimulus.	Color Seen.	After-image.
70°	Orange	Yel. orange	None
70°	Blue	Blue	None
70°	Gray	White	None
70°	Yellow	Yellow	None
80°	Orange	Unsat. yellow	None
80°	Blue	Pale blue	None
80°	Gray	No color	None
80°	Yellow	Light yellow	None
80°	Yellow	White	None
80°	Gray	Light	Dark
70°	Blue	Blue	None
70°	Yellow	Yellow	None
85°	Blue	Unsat. blue	None
80°	Orange	Yellow	None

The results for S, H, R and F show that when the general illumination is decreased by a single thickness of curtain the red, orange and yellow appear clearly yellow at the periphery. In the case of H the colors mentioned grew distinctly reddish as soon as the room was further darkened by a double curtain. CF saw the colors as distinctly reddish with both the single and the double curtain.[6] P saw them as reddish with the single curtain.[6] (No results were obtained for P with the double curtain.) F saw the colors as yellowish with both the single and the double curtain.

[6] Results not given. Observer C. F. is Dr. C. E. Ferree of Bryn Mawr College.

These results are less satisfactory than those obtained by other methods as the colors appeared less saturated than in any of the previous work. It is probable that the seeming irregularities are to be explained on the ground of individual variations. When the light is cut out by a single thickness of curtain both background and color are darkened, but the brightness contrast between the color and the background is still sufficiently strong to make the color appear relatively light and consequently yellowish to those observers who have the less strongly marked tendency to see red at the periphery. The observers who have a greater sensitivity to red see the stimulus as red when it has been slightly darkened (see section on individual variation, pp. 59–60).

In every case but that of F the colors were seen as reddish when the room was darkened by the double curtain, and F shows a less strongly marked tendency to see red at the periphery than any of the other observers except R.

The results seem to show that darkening the colors sufficiently will cause the colors to appear reddish even when the entire room is darkened. The reds and oranges are, however, less clear and saturated than when the stimulus is darkened by brightness contrast with the white ground.

(*c*) EFFECT OF CHANGING THE BRIGHTNESS OF THE STIMULUS WITHOUT CHANGING THE GENERAL ILLUMINATION OR THE BRIGHTNESS OF THE BACKGROUND.

Three methods were employed for varying the brightness of the stimulus without introducing any change in brightness of the background or in the general illumination. (1) The color was shaded by a dark screen placed above it, so that while the color was still easily distinguishable in central vision, it was decidedly darkened. (2) The brightness of the stimulus was increased or decreased by superimposing upon it the after-image of the black or the white screen used to cover the color before and after stimulations. (3) Black or white discs were combined with the stimulus on the electric color-mixer.

(*a*) *Darkening the Stimulus by Shading it with a Dark Screen.*—In the use of the first method the quality of the color

perceived in central vision was not affected, although the stimulus was noticeably darkened. The stimuli were given, as in our previous work, in irregular order, various colors as well as black, white and gray, being interposed between the red, orange and yellow stimuli. The following results were obtained with observers H and F.

TABLE VI.

OBSERVER H.[7]

(Results obtained at Bryn Mawr.)

Black Background. Stimulus Darkened by Black Cover. White Screen.

Fix. Pt.	Stimulus.	Color Seen.	After-image.
80°	Yellow	White	Light gray
75°	Yellow	Orange, like Or. disc.	Blue
70°	Yellow	No color	No after-image
70°	Yellow	Yellow orange	Blue
65°	Yellow	Yellow	Blue
75°	Orange	No color	Blue
75°	Orange	No color	Blue very faint
75°	Orange	Unsat. orange	Pale blue
70°	Orange	Orange red	Blue
65°	Orange	Sat. red like red disc	White
65°	Orange	Dark sat. maroon	Pale blue
65°	Orange	Sat. red like dark red of Hering series.	Blue
60°	Orange	Red like dk. red of series	Pale blue

TABLE VII.

OBSERVER F.[8]

Black Background. Stimulus Darkened by a Black Cover. White Screen.

(Results obtained at Bryn Mawr.)

Fix. Pt.	Stimulus.	Color Seen.	After-image.
85°	Yellow	None—just white	None
80°	Yellow	Dull yellow; grew red rapidly	None
75°	Yellow	Dull unsat. orange	Blue
65°	Yellow	Orange yellow	Deep blue
85°	Orange	Possibly red	None
80°	Orange	Dark red	None
75°	Orange	Dark brick red	Blue
70°	Orange	Dark sat. red	Blue
65°	Orange	Orange	None

[7] No results for red are given, as the red disc appeared simply as black at all the above fixation points, when it was darkened by this method.

[8] Red was seen simply as black in to 65 degrees. It was reported as a doubtful red once at 65°.

The results for both H and F show that the effect of darkening the yellow and orange by this method is to decrease their saturation. Certain of these stimuli appear reddish at the periphery. Other later results agree with those for H and F.

(β) *Projecting the After-image of a White or a Black Screen on the Stimulus.*—The platinum black and gray, and the Hering black and white backgrounds were used in this part of the experiment. The method of procedure was exactly the same as that already described except that the screen (X in the figure p. 16), used to cover the color before and after stimulation was varied, *i. e.*, both the black and the white screens were

Table VIII, A.

Observer H.[9]

Color seen is designated by letters, *e. g.*, R = red, O = orange, etc. The subscript letters indicate color of after-images.

Stimulus.	Backgr'd.	Screen.	55°	60°	65°	70°	75°	80°	85°	90°
Orange	White	White	RO_b O_b	R_b OR_b	$2OR_b$	$2R_b$	I_b	O_b		
"	"	Black	2O	RO O	RO OR	RO OY	I	I		
"	Black	White	RO	O	O	RO_b RO OR_b 2 O	RO_b O	O	RO_b OY_b I	
"	"	Black	OY	OY	2OY	2 O OY	O OY	O Y	OY Y III	Y
Yellow	White	White		RO_b	OR_b O_b OY_b	O_b		R_bR OR_b RO_b	III	
"	"	Black		$Y\text{-}O_b$	2Y Y_b	Y		2Y Y_b	2Y I_b	
"	Black	White		Y_b	Y_b	O_b	O_b OY			OY
"	"	Black		Y_b	Y_b	Y_b	2Y			Y

[9] These results were obtained at Bryn Mawr College. The backgrounds were Hering black and white instead of platinum. The fixation was held about three seconds before the stimulus was exposed.

used in each series of tests with a given background. The fixation was held for a period varying from three to ten seconds. As soon as the screen was removed, the brightness after-image, namely, black for the white screen, white for the black screen, was mixed with the stimulus color, thus causing the color to appear darker or lighter. A possible objection to this method is that an element of fatigue may be introduced by the somewhat continued maintenance of the fixation. The observers, however, reported a complete lack of any subjective evidence of such fatigue.

The following tables give the results for observers, H, F and W. The tables for H and F are followed by a summary showing the number of times a stimulus was seen in a given color tone under given brightness conditions (p. 33).

B.

Observer F.

Stimulus.	Backgr'd.	Slide.	50°	55°	60°	65°	70°	75°	80°	85°	90°
Orange	White	White	R_b	RO R_b	RO_b R	OR_b	?O_b	R_b	I	I	I
"	"	Black	O- RO_b	O- RO_b R_b	O_b	R RO O_b	OR I	II		I	I
"	Black	White				YO_b	Y OY	O	O	Y-O	
"	"	Black				YO_b	OY	OY_b	Y_b	Y	
Yellow	White	White	Y_b	2 Y_b	O_b	2Y_b	O_b O I	II	III	II	I
"	"	Black	Y_b	2 Y_b	Y_b	Y_b	3Y_b		IO Y_b	II_b Y	
"	Black	White				Y_b	Y_b	Y	Y_b	I_b	
"	"	Black				Y_b	Y_b	Y_b	Y_b	Y	

The results for H show a constant tendency on the part of orange and yellow to appear redder when the dark after-image of the white screen is mixed with the stimulus color than when the white after-image of the black screen is mixed with it. The most striking results are those for yellow with the white background. In this case yellow appears as either orange or red

Table IX.

Observer H.

Number of Times the Stimulus was Seen as R (Red), etc.

Background.	Slide.	R.	OR.	RO.	O.	YO.	OY.	Y.	Not Seen.	Total.
					Stimulus, Yellow.					
White	White	2	2	2	2	—	1	—	3	12
White	Black	—	—	—	—	—	—	10	1	11
Black	White	—	—	—	3	—	2	2	—	7
Black	Black	—	—	—	—	—	—	7	—	7
					Stimulus, Orange.					
White	White	3	3	1	2	—	—	—	1	10
White	Black	—	1	3	3	—	1	—	2	10
Black	White	—	1	5	6	—	1	—	1	14
Black	Black	—	—	—	4	—	7	3	3	17

Table X.

Observer F.

Number of Times the Stimulus was Seen as R (Red), etc.

Background.	Slide.	R.	OR.	RO.	O.	YO.	OY.	Y.	Not Seen.	Total.
					Stimulus, Yellow.					
White	White	—	—	—	3	—	—	5	9	17
White	White	—	—	—	1	—	—	10	3	14
Black	White	—	—	—	—	—	—	4	1	5
Black	Black	—	—	—	—	—	—	4	1	5
					Stimulus, Orange.					
White	White	5	—	2	2	—	—	—	4	13
White	Black	2	1	3	2	—	—	—	5	13
Black	White	—	—	—	2	2	1	—	—	5
Black	Black	—	—	—	—	1	2	2	—	5

Table XI.

Observer W.

Fix. Pt.	Stimulus.	Black Screen. Color Seen.	White Screen. Color Seen.
		Gray Background.	
80°	Unsat. orange	Unsat. or. yellow	White
80°	Unsat. orange	Unsat. or. yellow	White
75°	Unsat. orange	Bright orange	Orange to bright red
75°	Unsat. orange	Orange	....
80°	Unsat. orange	Yellow to orange	Dark saturated red.
		Black Background.	
85°	Orange	Orange	Indistinct, some reddish
80°	Orange	Orange	Orange
85°	Red	Orange	Black
85°	Red	Orange	Orange
80°	Red	Orange	Red orange

The fixation was held for 10 seconds before the screen was removed in all cases except the last with orange. In this instance the screen was removed after a 5 seconds fixation.

without exception when the color is darkened by the black after-image of the white screen, and invariably as yellow when the stimulus is brightened by the white after-image of the black screen. At 60° with the black screen the color appeared once as a yellow when first exposed, but changed to orange (Y–O). This may be due to the fact that as the effect of the white after-image was lost the color grew darker.

The results for F are much less conclusive than those for H. Orange appears reddish with a white background and yellowish with a dark background, regardless of the brightness of the screen. The results show, however, a slightly greater tendency for the stimuli to appear reddish with the light than with the dark screen.

The results for W are somewhat incomplete. They were obtained in the course of one hour's experimentation, and are given just as recorded, except that all results for stimuli other then orange are omitted. Violet, blue and gray were included in the series as given. The results show a slight but decided effect of the brightness changes produced. Orange tends to appear redder with either background whenever the black after-image of the white screen is mixed with the red or orange stimulus.

The fact that the results for W and H show a more positive effect of the change produced on the color by the brightness after-image than is shown by the results for F simply affords an illustration of individual variation. Such individual variations are shown throughout the work (cf. pp. 59–60) and are sufficient to make a factor which is influential in one case, ineffective in another. The results for F and R seem to show that their reactions are always less easily modified by brightness changes than those of the other observers. The modifications are, however, very marked and exactly similar to those obtained by other observers when the brightness changes are sufficiently great.

(γ) *Mixing Black or White with the Stimulus on the Electric Color Mixer.*—The stimulus color was mixed with given amounts of white or black, by means of the electric color mixer. The difficulty in this case is that the saturation of the color is noticeably decreased.

The results are given of work with observers W, R and F. It is true that the results are few in number, but the facts that the entire series with any given background was obtained on the same day under identical light conditions, and that the dark and light mixtures were alternated, without any knowledge on the part of the observer concerning the stimuli employed, make these results significant.

Table XII.

Observer W.

Black Background.

Fix. Pt.	260° Red + 100° White.	Fully Saturated Red.	260° Red + 100° Black.
90°	Yellow	Yel. orange	Yel. orange
85°	Yellow	Orange	Orange
80°	Orange	Orange	Orange

Gray Background.

Fix. Pt.	180° Red + 180° White.	180° Red + 180° Black.
80°	Orange	Black
75°	Scarlet red	Dark red
70°	Yellow orange	Brick red. (102° black instead of 180°.)

Black Background.

Fix. Pt.	260° Orange + 100° White.	360° Orange.	260° Orange + 100° Black.
90°	Yellow	Or. yellow	Or. yellow
85°	Orange yellow	Or. yellow	Or. yellow

Gray Background.

Fix. Pt.	280° Orange + 80° White.	280° Orange + 80° Black.
75°	Scarlet red	Brick red

Black Background.

Fix. Pt.	180° Yellow + 180° White.	180° Yellow + 180° Black.
75°	Colorless	Yellow
80°		Colorless

The description of the stimulus is given at the head of each column (*i. e.*, 260° red + 100° white, etc.). The color seen is given opposite the fixation point (90, etc.) and directly under the description of the stimulus.

TABLE XIII.

OBSERVER F.

Gray Background.

Red 246° Black 58° White 56°	Matched background in brightness.	At 80° only blue after-image, no color for stimulus. At 70° good medium red.
Black 114° Red 246°	Darker than background.	At 70° good medium red.
White 114° Red 246°	Lighter than background	At 70° orange.

TABLE XIV.

80°	Orange yellow 252° Black 58° White 50°	Good clear or. yellow.	B. violet after-image.
80°	Orange yellow 252° Black 108°	Good clear or. yellow.	B. violet after-image.
80°	Orange yellow 252° White 108°	Or. yellow like above only lighter.	Violet after-image.

The results for observers W and F indicate a tendency on the part of the darker color to appear more reddish than the lighter color. R's results are not given, as the color fields were so diminished by the decrease in saturation involved in this method, that the color was not seen far enough out at the periphery to justify any conclusions.

In the case of W, whose results were obtained with both the black and the gray backgrounds, the change in the color-tone of the stimulus is decided only with the black background. With this background, light red (*i. e.*, red + 180° white) is seen as yellow at 90° and at 85° while at the same points the pure red and the red + 180° of black are seen as yellowish orange and orange. Orange + 100° of white is seen as yellow at 90°, while orange and orange + 100° of black are seen as orange-yellow at the same point.

F's results are given for red and orange yellow with the gray background. The amount of the stimulus color was kept the same in all cases, *i. e.*, 246°, but it was first mixed with 114° of black and white in such proportions that it matched

the background in brightness. The whole sector of 114° was next made black and then white. The results for red show that the two darker colors were seen as red, while the lighter color was seen as orange at the same point. The few results with orange-yellow are entirely negative.

The only conclusion which we can draw from these results is that the changes in the stimulus color produced by this method are primarily a decrease in the saturation and in certain cases a shift of the color toward red.[10]

2. *Effect of Brightness on the After-image.*

Explanatory Statement.—*Perceived* will be used to describe the stimulus when it appeared to the observer as colored, *unperceived* when it appeared colorless. *Background* will be used to designate the campimeter screen (*E* in figure, p. 16), and *projection-ground* to indicate the screen which covers the color before and after stimulation (*x* in figure, p. 16). No distinction was made between the two screens in our earlier papers as they were both of the same brightness and so formed one continuous background.

The conclusions concerning after-images are based (1) on the results given in the tables at the end of Section A (pp. 50–58), which give the characteristic after-images observed on screens (*i. e.*, projection grounds) matching the various backgrounds in brightness; (2) on the results reported in the section on the 'Effect of Decreasing the General Illumination' (pp. 24ff.); (3) on the results reported on pages 40–41 and 31–33, which show the effect of changing the brightness of the projection-ground without changing the brightness of the background.

Results.—Characteristic after-images followed perceived color stimuli almost without exception, when the observations were made under any of the following conditions: (1) With the white, gray or black backgrounds in full illumination.

[10] Other results more recent than those given above, agree with those reported in the entire section on the effect of darkening the stimulus by methods other than brightness contrast (pp. 24ff.). In all cases, however, the color appeared poorly saturated and the change in color tone was less marked than that produced by brightness contrast.

(This statement does not apply to the results obtained with the black background in the Bryn Mawr Laboratory or to those obtained with the carmine stimulus on the black background in the Chicago Laboratory). (2) With the dark background darkened by the black hood, when the stimulus color was covered after the stimulation by simply pushing the slide (*x* in figure, p. 16) back over it. In this case the general field about the observer was very dark, but the projection-ground received full illumination and was further brightened by contrast with the dark background. It may be mentioned here that after-images were entirely absent when a black cardboard was slid directly over the opening in the background, so that the entire field was dark immediately after the stimulation.

After-images were relatively infrequent, even for clearly perceived color stimuli, when the illumination of the entire room was decreased, either by darkening the room by means of the black curtain or by general weather conditions. In the work with H and F at Bryn Mawr a smaller percentage of after-images was obtained with the dark than with the light background (cf. pp. 31–32).

In all of the above cases the after-image exhibited a most decided decrease in saturation as the illumination was decreased. That is, the most saturated after-images were obtained with the white background, in full illumination, between the hours of nine in the morning and three in the afternoon. The after-images, under these conditions were reported by most observers to be either equal to the stimulus in saturation or else as decidedly more saturated than the stimulus. The after-images with the dark background were reported as decidedly less saturated than the stimuli and as very much less saturated than those obtained with the white background. As the general illumination is decreased, the after-images not only decrease in number but become very poorly saturated when perceived. The main exception to the above statement occurs in the case of the after-image for blue and green-blue on the dark background and in a few instances for these stimuli in decreased illumination. The after-image, under these conditions, was a deep, saturated red for most of our observers and a fairly saturated orange

for the others. The observers who experienced the red after-image, described it as the most saturated after-image obtained throughout the series. Even in the case of this red after-image, however, there seemed to be a special brightness of background and illumination which gave the most saturated after-image, and any decrease in the illumination below this point was followed by a corresponding decrease in the saturation of the after-image.

In addition to the work reported in the tables in this paper a considerable amount of work was done on rather cloudy days or after three or four o'clock in the afternoon. The after-images were relatively infrequent or poorly saturated in all of these cases. Even working in a room with black walls seemed to have this same effect on the after-image.

With the dark and gray projection grounds the after-images for orange and red tended to appear greenish in the paracentral and less extreme peripheral regions, though they still appeared blue in the more peripheral regions. The after-image for violet appeared as green in the inner peripheral zone and as green or yellow or, in a few cases, as a very unsaturated orange in the outer peripheral regions. The most striking change occurred in the appearance of the after-images for blue and green-blue. With the dark background these were an orange or a very well-saturated red at the extreme periphery. (The red was invariably described as more saturated than the orange.)

In order to determine whether the color changes were due to the darkening of the after-image itself, or to the variations in the brightness of the background, or to changes in the general illumination, the after-images were projected, first on a light and then on a dark projection ground, throughout an entire series in which the background was not changed. Results were obtained according to this method with both the light and the dark backgrounds. Thus we have an entire series of results, showing the appearance of both light and dark after-images with the white background, and a similar series with the dark background. It should be stated here that this experiment is suggested by Misses Thompson and Gordon, though only carried out by them in central vision.

The results obtained for red, orange and yellow stimuli, according to this method are given on pages 31–33. As the after-image was invariably blue with both backgrounds the results are not repeated here. The results obtained with blue stimuli are given in the following tables.

The Arabic numerals give the number of times the stimulus was seen as blue, the Roman numerals the number of times the stimulus was seen simply as brightness. The after-images are designated by the suffixes y (yellow), r (red), etc.

Table XV, A.

Observer W.

Stimulus.	Background.	Projection.	75°	80°	85°
Blue	Black	Black	1_o	2_o	1_o
	"	White	1_y	1, 1_y	1_y

B.

Observer R.

Stimulus.	Background.	Projection.	60°	65°	70°	75°	80°	85°	90°
Blue	Black	Black	1_{g-r}	1_y	1_{go}	2_{yg}	1, 1_o	4 1_o	2, I, 1_{o-g}
"	Black + Hood	"			1_{gy}			2_o, 1_{yo}	1_o
"	Black	White			1_{oy}		3	1_{oy}	1, 2_y
"	White	White	3_y, 1_o, 2	3_y, 1_g, 1	1_y	1_y	1_y, 2	1_y, 2	I, 1
"	Black + Curtain	Black					1_{ro} 1	2, $1_?$, 1_{go}	1

C.

Observer H.[11]

Stimulus.	Background.	Projection.	55°	60°	65°	70°	75°	80°	85°
Blue	White	White	3_y	3_y	4_y	2_y, II	II_y	IV	III
"	"	Black	2_o, 1_{ro}	2, 1_r	2_{or}, 1_y, 3	2, 1_{-}, II	3, I	IV	III
"	Black	White		1_{-}	2_y	1_{-}		1_y	1
"	"	Black		1_{ro}	1_r, 1_o	1_o		1	1

[11] Results obtained at Bryn Mawr.

D.

OBSERVER C.

Stimulus.	Back-ground.	Projection Ground.	60°	65°	70°	75°	80°	85°	90°	92.5°
Blue	Black	Black			1_r	1_r	2_r	1_r	$1_{or}, 2_r$	1_r?
"	Black + Curtain	"		1_r			1_r	2_r	1_r	
"	Black	Gray					1_{yo}	1_{ro-y}		
"	"	White					1_{ro}	1_{ro}	1_{r-y}	
"	White	"					2_y	$2_o 1_y$	2_{oy} II	III
"	Black + Hood	Black					1	$1_r 1_{y-r}$	$2_r 1$	

Red after-image described as exactly like red paper, more intense than stimulus. O greatly disturbed by red as a.-i. for blue. Especially brilliant with black curtain.

E.

OBSERVER P.

Stimulus.	Back-ground.	Projection Ground.	60°	65°	70°	75°	80°	85°	90°	92.5°
Blue	Black	Black[12]					2_r	2_r	1_r	
"	Black + Hood	"					3_r	1_r	1_r	
"	Black	Gray								
"	"	White[13]					2_y	2_y	(1)	
"	White	"		1_y	1_y	1_y	1_y	II	II 1_y	

F.

OBSERVER F.

Stimulus.	Back-ground.	Projection Ground.	60°	65°	70°	75°	80°	85°	90°	92.5
Blue	Black	Black[14]				1_r	1	1_r, 3	1	
"	Black + Hood	"		2_y	1_o	1_{or}, 1_{yo}	1_{or}, 1_{ro}, 1_o	3_o, 1_o	1_o	
"	Black	Gray				1_{yo}	1_{yo}, 1_o	1?	1	
"	"	White		1_{oy}	1_{oy}	1_y	2_{oy}	1?, 1_{oy}	$1_{(y)}$	
"	White	"	$1_{yg} 1_y 1_{y-o}$[15]					3_y, 1_{yg}	1, 1_y, 1_{oy}	

[12] Red after-image = 'Brilliant decided red.'

[13] Yellow after-image = 'Very poorly saturated.'

[14] Red after-image more saturated than yellow.

[15] Yellow, grew orange.

The results for W, R, C and P show that the after-image is almost invariably yellow when projected on the white screen and orange or pure red when projected on the dark screen. No results were obtained for these observers with the white background and black projection-ground. In the experiments with H and F the after-image was yellow when projected on the white screen and orange or red when projected on the dark screen, with the white as well as with the dark backgrounds.

Although the after-image shifts toward red, in all cases with the dark projection-ground, the effect of the local brightness change thus produced was greater for some observers than for others. Under the conditions just described (*i. e.*, with the dark projection-ground) the after-image for P and C was a pure red which was so well saturated that both observers asked if a red stimulus had not been given after the blue. The observers were the more surprised as they expected a yellow after-image. The red was identified with the red of the Hering series. H showed a decided decrease in the percentage of after-images with the dark background and the dark projection-ground, but when seen, they were red or orange with two exceptions. (The after-image was yellow twice with the dark projection-ground and white background.) F's after-images were always red or orange, the red being much more saturated than any of the yellows experienced on the white projection-ground. The after-images for W were orange in the few cases in which the after-image for blue was projected on the dark screen. R's results show less alteration with change of screen than do those of any other observer. There is, however, a shift toward orange with the dark projection-ground. R was not always sure of the color of the after-image, being at times doubtful whether it was tinged with green or orange.

The results just reported seem to show that the color-tone of the after-image is more dependent upon the brightness of the projection-ground (local brightness conditions) than upon the contrasting brightness of the surrounding background.

That the phenomena reported here are genuine after-images is shown by the following facts.

1. The colors are reported as perfectly clear and distinct by

all observers, with the few exceptions of the unsaturated images on the dark background. Observer R had nearly completed the series before she discovered that a second color was not actually used as a stimulus. She had been especially cautioned not to move her eye until every trace of color had disappeared, and consequently never saw the gray screen until the after-image had completely disappeared. One day, however, just at the close of the year, she suddenly exclaimed: "Why, isn't that funny—I looked back accidentally while the yellow was still there and there wasn't any color!" She was greatly surprised. She always spoke of the stimulus color as the 'color going in' and the after-image as the 'color going out.' When the colored after-image followed the unperceived color stimulus, she always reported 'gray,' 'black' or 'white' 'going in' and 'blue,' 'yellow,' etc., 'going out.' She was astonished to discover at the close of the experiment that a second stimulus had not been given throughout the work. In the same way observers C and Y asked if a second color had not been given when the red after-image followed the blue stimulus on the dark background, first, because the after-image was so well staturated, and second, because it was not the color complementary to the blue. As C expressed it: "I haven't any business to see that red way out there, especially as an after-image for that blue, but I never saw a better red in my life."

2. Although the stimuli were given in an irregular order and the observer was kept in ignorance concerning the nature of the stimulus, the after-image was always the characteristic one for the stimulus under the given brightness conditions, even when the stimulus color was not distinguished.

3. Black, white and gray were frequently given as stimuli, but were never followed by colored after-images, with a single exception in the case of observer C, who reported an unsaturated red after-image in a few instances when a dark screen followed a white stimulus. It may be well to state here that our method of procedure differed essentially from that of either Hellpach or Baird, in that both of these investigators gave the same stimulus in successive tests throughout a series, while we gave the stimuli in irregular order, seldom using the same stimulus twice in suc-

cession, and frequently introduced brightness stimuli, without the knowledge of the observer, into the series.

Our general conclusions based on all our work with peripheral after-images, are as follows:

(*a*) The relative frequency with which characteristic colored after-images follow color stimuli and the saturation of these after-images are directly dependent on brightness conditions. As the general illumination or the brightness of the projection-screen is decreased, the after-images become at first less saturated and finally less frequent. This decrease in the saturation of the after-image is much more marked than the corresponding decrease in the saturation of the stimulus color. That these results are due to the brightness conditions under which the after-image is observed is shown by the following facts: (1) That a decrease in the illumination, which has little effect on the appearance of the stimulus color, has a very decided effect on the saturation of the after-image; (2) that the after-image, with the exception of red, invariably appears less saturated on the dark than on the light background, and yet this is just the condition under which all the stimuli except red and orange appear most saturated; (3) that, in the observations made under the black hood, fairly well-saturated after-images followed the stimuli when the after-image was projected through the campimeter opening on a screen which received full illumination, but that after-images were entirely absent when the observation of the stimuli was made exactly as in the previous case save that the light was cut off from the observer by placing a black card directly over the circular opening in the campimeter, so that any possible after-images would necessarily be observed on an entirely darkened field; (4) that the after-images appear most saturated on a particular projection-ground, even when no other change is made in the brightness conditions.

(*b*) The color-tone of the after-image for certain colors is directly dependent on the brightness of the projection-ground. The after-image for blue and blue-green is yellow on the white projection-ground and red or orange on the dark projection-ground; for violet, greenish on the dark projection-ground and

yellow on the light projection-ground; for red, orange and yellow, blue on both the light and dark backgrounds except in the paracentral zone.

(*c*) Characteristic after-images followed unperceived color stimuli in some cases with the light projection-ground and with full illumination of a bright day. These after-images were never obtained on cloudy days or later than three or four o'clock on bright days. For illustrations of these after-images see Tables XX. and XXI.

3. *Comparison of the Effect of Brightness Contrast with that of Color Contrast.*

Although the background appeared entirely colorless there seemed to be the possibility that some subliminal color might be present and be effective in producing the results described. To determine whether the results could be due to color contrast, a series of experiments was made with the fully saturated Hering green as a background. Green was chosen for the background because, in central vision, green is the contrast color for red and so would tend to enhance the red in any stimulus, and produce results similar to those we obtained in peripheral vision when the color was darkened by contrast with the white background. It is obvious that, if our results in peripheral vision are due to the presence of subliminal green in the background, the use of a fully saturated green background might be expected to increase this effect.

The results obtained are given in Tables XVIII and XIX, pp. 48 and 49. The summaries given on pages 46 and 47 show the number of times the orange and yellow stimuli and the after-image for blue appeared as red, orange or yellow with the different backgrounds.

The results for both H and F give no evidence of color contrast with the green background, in spite of the fact that the color contrast was so strong in central vision that both the black and the white screen appeared reddish. (This reddish tinge is completely lost when the eye is turned out through an angle of 45 to 50 degrees.) It will be seen on examination of the results that the orange and the yellow stimuli show a de-

cidedly greater tendency to appear red with the white than with the green background. In fact, the results with the green background represent a mean between the results obtained with the white and those obtained with the black backgrounds. This is just what we should expect as the result of brightness contrast, since the green is matched in brightness by a light middle gray, but it is just the opposite to what we should expect as the result of color contrast.

The change produced in the brightness of the color by throwing the after-image of a white or a black screen upon it, is fully as marked with the green background as with any other background. Orange and yellow appear more reddish when darkened by the black after-image than when brightened by the white after-image. (See pp. 46–47 for summary of results.) With the green background the after-image for blue is invariably yellow when it is projected on the white screen, and orange or red when it is projected on the dark screen.

These results show (1) that the effect produced on the orange and yellow stimuli and on the after-image for blue were not due to any subliminal green in the background, and (2) that the brightness of a colored background is effective in determining the color seen, even though the color of this background is ineffective.

Table XVI

Observer H.

Stimulus, Orange.

These results are simply a summary of the Tables XVIII and XIX.

Color Seen Designated by Letters—*i. e.*, R = Red, etc.

Background.	Slide.	R.	OR.	RO.	O.	OY.	Y.	No Color Seen.	Total.
White	White	3	3	1	2	—	—	1	10
White	Black	—	1	3	3	1	—	2	10
Green	White	2	1	2	2	—	—	2	9
Green	Black	—	1	4	2	—	—	2	9
Black	White	—	1	5	6	1	—	1	14
Black	Black	—	—	—	4	7	3	3	17

TABLE XVI (*Continued*).

Stimulus, Yellow.

White	White	2	2	2	2	1	—	3	12
White	Black	—	—	—	—	—	10	1	11
Green	White	—	1	—	3	2	2	1	9
Green	Black	—	—	—	—	2	7	—	9
Black	White	—	—	—	3	2	2	—	7
Black	Black	—	—	—	—	—	7	—	7

Stimulus, Blue.

After-image Designated by Name—Yellow, etc.

Background.	Slide.	Yellow.	Red or Orange.	No After-image.	Total.
White	White	14	—	9	23
White	Black	1	5	20	26
Green	White	13	—	1	14
Green	Black	—	5	9	14
Black	White	5	—	1	6
Black	Black	—	4	2	6

TABLE XVII

OBSERVER F.

Stimulus, Orange.

Color Seen Designated by Letter—R = Red, etc.

Background.	Slide.	R.	OR.	RO.	O.	YO.	OY.	Y.	Not seen.	Total.
White	White	5	—	2	2	—	—	—	4	13
White	Black	2	1	3	2	—	—	—	5	13
Green	White	1	—	2	7	—	—	—	3	13
Green	Black	1	—	1	6	—	1	2	2	13
Black	White	—	—	—	2	3	—	—	—	5
Black	Black	—	—	—	—	—	3	2	—	5

Stimulus, Yellow.

		O.	YO.	OY.	Y.	Not Seen.	Total.
White	White	3	—	—	5	9	17
White	Black	1	—	—	10	3	14
Green	White	1	1	—	11	—	13
Green	Black	1	—	1	11	—	13
Black	White	—	—	—	4	1	5
Black	Black	—	—	—	5	—	5

Stimulus, Blue.

After-image Represented by Letter—R = Red, etc.

Background.	Slide.	R.	OR.	O.	OY.	Y.	None Seen.	Total.
White	White	—	—	—	—	15	6	21
White	Black	2	—	2	—	—	17	21
Green	White	—	—	—	—	12	1	13
Green	Black	1	2	1	1	—	8	13
Black	White	—	—	—	—	4	1	5
Black	Black	—	—	1	—	—	4	5

TABLE XVIII

OBSERVER H.[16]

Size of Stimulus = 12 mm.

Stimulus.	Color Seen.	Back-ground.	Projection Ground.	50°	55°	60°	65°	70°	75°	80°	85°	90°
Blue	Blue	White	White		3_y	3_y	4_y	2_y, II	II_y	IV	III	
"	"	"	Black		2_o, 1_{ro}	2, 1_r	2_{or}, 1_y, 3	2, II, I_y	3, I	IV	III	
"	"	Green	White		3_y	3_y	3_y	2_y	2_y	I		
"	"	"	Black		1_{ro}, 1_o, 1	2, 1_r	2_o, 1	2	2	I		
"	"	Black	White			1_y	2_y	1_y		1_y	1	
"	"	"	Black			1_{ro}	1_r, 1_o	1_o		1	1	
Orange		White	White		O_b, RO_b	R_b, OR_b	$2OR_b$	$2R_b$	I_b	O_b		
"	Designated	"	Black		2O	RO, O	RO, OR	RO, OY	I	I		
"	by letters	Green	White		R_b, RO_b	RO_b	$2O_b$	OR_b, R_b	I	I		
"	R = Red	"	Black		OR_b, O	RO_b	I, O_b	2RO	RO	I		
"	OR=Or-Red RO=Red-Or O=Orange	Black	White		RO	O_b	O_b	RO_b, RO, 2O OR_b	RO_b, O	O	RO_b, I, OY_b	
"	Y=Yellow etc.	"	Black		OY_b	OY_b	2OY	2O, OY	O, OY	O, Y	OY, Y, III	Y
Yellow		White	White			RO_b	OR_b, O_b, OY_b	O_b		R_b, R, OR_b, RO_b	III	
"		"	Black			Y-O_b	2Y, Y_b	Y		2Y, Y_b	2Y,I	
"		Green	White		Y_b	OY_b	O_b, YO_b	Y_b	OR_b, I_b	$2O_b$		
"		"	Black		Y_b	Y	Y, Y_b	Y	2Y	2OY		
"		Black	White		Y_b	Y_b	O_b	O_b, OY_b	O_b			OY
"		"	Black		Y_b	Y_b	Y_b	2Y	Y_b			Y

[16] In Tables XVI. and XVII., as in previous tables, Arabic numerals show the number of times a stimulus is seen as colored, Roman numerals the number of times it is seen as brightness simply. Subscripts indicate after-image colors. In the parts of the tables reporting the observations upon orange and yellow, capital letters designate the colors seen. When a stimulus is first seen as one color which then turns into another, the fact is indicated thus, 'Y-O,' meaning yellow turning to orange.

TABLE XIX

OBSERVER F.

Size of Stimulus = 12 mm.

Stimulus.	Color Seen.	Background.	Projection Ground.	50°	55°	60°	65°	70°	75°	80°	85°	90°
Blue	Blue	White	White	1_y	3_y		3_y, II	4_y	1_y, I	1_y, I	I_y, I	1_y, I
"	"	"	Black	1_o	1_r, 2		1_o, 4	1_r, 2	2, I	II	II, 1	1
"	"	Green	White		2_y	2_y	2_y	2_y	2_y	1_y, 1	1_y	
"	"	"	Black		1_{or}, 1_{oy}	1_o, 1_r	2	1_{or}, 1	2	2	1	
"	"	Black	White				1_y		1_y	I_y	1	1_y
"	"	"	Black				1_o		1	I	1	?
Orange		White	White	R_b	R_b, RO	RO_b, R	R_b, O	?, O_b	R_b	I	I	I
"	Designated by letters	"	Black	O-RO_b	O-RO_b, R_b	O_b	R, RO, O_b	OR, I	II		I	I
"	R=red	Green	White		O_b	2O_b, O	RO_b, O	RO_b, O_b	I, R_b	I, O	I	
"	O=Orange	"	Black		O_b	2O, R_b	O_b, OY_b	RO_b, O	O, Y	I, Y	I	
"	etc.	Black	White				YO_b	Y-YO	O	O	Y-O	
"		"	Black				YO_b	OY	OY_b	Y_b	Y	
Yellow		White	White	Y_b	2Y_b	O_b	2Y_b	O_b, O, I	II	III	II	I
"		"	Black	Y_b	2Y_b	Y_b	Y_b	3Y_b		I, O, Y_b	I, I_b, Y	
"		Green	White		Y_b, YO_b	Y_b, Y	O_b, Y	2Y_b	2Y_b	2Y_b	Y	
"		"	Black		2Y_b	Y_b, O	2Y_b	2Y_b	OY_b, Y_b	Y, Y_b	Y	
"		Black	White				Y_b	Y_b	Y	Y_b	I_b	
"		"	Black				Y_b	Y_b	Y_b	Y_b	Y	

Explanation of Tables XX–XXIV inclusive.—The stimulus given is designated in the vertical column marked 'stimulus,' the color-tone as it appeared to the observer in the vertical column marked 'color seen.'

The degree of eccentricity at which the stimulus was given is designated by the figures at the top of the tables (*i. e.*, 60°, 65°, etc.).

The number of times the stimulus was observed at a given fixation point is shown by the figures in the vertical columns, the tone of the colors as seen being designated by the horizontal column in which the figure is placed. The Arabic numerals give the number of times the stimulus was seen as a color, the Roman numerals the number of times the stimulus failed to be seen as a color. Numerals in parentheses represent judgments about which the observer was doubtful.

The suffixes (*i. e.*, 1_b, etc.) designate the character of the after-images perceived. R, red; Y, yellow; G, green, etc. BG, blue-green; OY, orange-yellow, etc. G-O means that the observer was unable to tell whether the after-image was green or orange, or that the two colors were not fused.

All observations were made with the nasal half-meridian.

Table XX, A.

Observer P.

White Background.

Stimulus.	Color Seen.	Size of Stimulus.	60°	65°	70°	75°	80°	85°	90°
Yellow	Yellow	12 mm.							I
"	Red	"	1_b	1_b	1_b	1_b	1_b	2_b	$1_b(1_b)$
"	Yellow	5 mm.			$(I)_b$	$(IV)_{(b)}$	$(II)_{(b)}$	III(I)	I
"	Red	"	2_g	(1_b)	3_b				
Or.-Yel.	Or.-Yel.	12 mm.							
"	Red	"	1_b	1_b	1_b	1_b	1_b	3_b	2_b
Orange	Orange	"							
"	Red	"	1_b	1_b	1_b	1_b		2_b,1	3_b
"	Orange	5 mm.							
"	Red	"			1	1,1_b	II		
Red	"	12 mm.				1		2	
Blue	Blue	"		1_y	1_y	1_y	1_y	$1_?$,I	II,I_y
"	. "	5 mm.	2_y,I	(I_y),I_y	II_y	I	II		

TABLE XX, B.

OBSERVER C.

White Background.

Stimulus.	Color Seen.	Size of Stimulus.	70°	75°	80°	85°	90°	92.5°
Red	Red	12 mm.			1_b	I		
Orange	Orange	"					I_b	1_b
"	Red	"			$1,1_b$	$(1)_b,1$	$2_b,1(1_b)$	$(1)_b,1_b$
Or.-Yel.	Or.-Yel.	"					I,I_b	
"	Red	"			2_b	4_b	1_{gb}	
Yellow	Orange	"				1		
"	Red	"			1	1		
Blue	Blue	"			2_y	$1_y,2_o$	$II,2_{yo}$	III

TABLE XXI, A.

OBSERVER Y.

White Background.

Size of Stimulus, 12 mm.

Stimulus.	Color Seen.	75°	80°	85°	90°
Red	Red		3_{gb}	$(1)_{gb},1_b$	
Orange	Orange				
"	Red		2_{gb}	2_{gb}	
Or.-Yel.	Or.-Yel.				
"	Or.-Red		2_{gb}		
"	Red		1_{gb}	$(1),1_b,1$	(1)
Yellow	Yellow				
"	Red		1_b	1_b	(1)
Blue	Blue		1_y	$(1_y),1_y$	I,I_y

(*Note.*—The G. B. after-image was almost pure blue.)

B.

OBSERVER F.

White Background.

Size of Stimulus, 5 mm.

Stimulus.	Color Seen.	50°	55°	60°	65°	70°	75°	80°	85°	90°
Red	Red				I_b	I_b,I	I			I
Orange	Orange			I_b	II_b,I		I_b			I
"	Red	1_b	1_b	1_b		$1,1_b$				
Yellow	Yellow		I_b		I_b	II	I_b,I			
"	Orange	1		1_b	1_b					

Blue not seen beyond 60°.

C.

Observer R.

White Background.

Size of Stimulus, 12 mm.

Stimulus.	Color Seen.	45°	50°	55°	60°	65°	70°	75°	80°	85°	90°	95°
Red	Red				1_b	III, 1	II_b, I, 1					
Orange	Orange				2_b^r	1_b^r	3_b, 1	I		I	I	
"	Red					1_b		1_b	2_b	1_b	1	
Or.-Yel.	Or.-Yel.				2_b		2_b			I	I	
"	Orange				1_b^r	1_b	1^r	1_b^r	2_b	1_b	1_b	
"	Red								1_b			

D.

Observer A.

White Background.

Size of Stimulus, 12 mm.

Stimulus.	Color Seen.	45°	50°	55°	60°	65°	70°	75°	80°	85°	90°	95°
Red	Red		1_b	1_b					1_b			
Orange	Orange								I_b	II_b		
"	Red			2_b	1_b							
Or.-Yel.	Or.-Yel.								I_b, I			
"	Orange											
"	Red			2_b	2_b			1_b	1_b	1_b		
Blue				1_y	2_y			1_y	2, 1_y	?, 1_y		

E.

Observer Pr.

White Background.

Size of Stimulus, 12 mm.

Stimulus.	Color Seen.	65°	70°	75°	80°	85°	90°
Red	Red				I	I	I
Orange	Orange				I	I	I
"	*Red*			3		1	
Or.-Yellow	Or.-Yellow						
"	Orange		1	1_b	1_b, 1	4	
"	Red						
Yellow	Yellow						
"	Orange			1_b		2	
Blue	Blue					1_y	1_y, II
Grey	Grey				1	1	1

TABLE XXII.[17]

OBSERVER P.

Dark Background. Size of Stimulus, 5 mm.

Stimulus, or. yellow.
  Seen as yellow 60°–85° (inclusive) After-image blue.
  Not seen 90° No after-image
Stimulus, orange.
Background, dark.
  Seen as yellow 60°–90° After-image blue.
    (At 80° seen twice as orange.)
Dark background and black hood.
  Seen as yellow 70°–90°
    (Seen as orange once at 80°.)
Stimulus, red.
Dark background.
  Peculiar unfused mixture of red and yellow 60°–85°
  Not seen 90°
Dark background and black hood.
  Orange or orange yellow 70°–85°
  Not seen 90°

TABLE XXIII.

A.

OBSERVER Y.

Dark Background.

Size of Stimulus, 12 mm.

Stimulus, red.
  Seen as orange 60°–65°
  Seen as orange yellow 75°–90°
Stimulus, orange.
  Seen as orange 60°–75°
  Seen as orange yellow 85°–90°
Stimulus, orange yellow.
  Seen as orange yellow 60°
  Seen as yellow 75°–90°

B.

OBSERVER C.

Dark Background.

Size of Stimulus, 12 mm.

Stimulus, red.
  Peculiar unfused mixture of red and yellow—film of red over bright yellow 70°–90°
Stimulus, orange.
  Same unfused red and yellow 85°–90°
Stimulus, orange yellow.
  Unfused mixture orange and yellow 70°–80°
Stimulus, yellow.
  Seen as golden yellow or slightly orange yellow 70°–92.5°

[17] The stimuli were not given nearer the center than the innermost point designated in the tables, *i. e.*, orange for observer P was not given at a less degree of eccentricity than 70° with the dark background and hood. In most cases each stimulus was given only twice at each fixation point.

Table XXIV, A.

Observer R.

Size of Stimulus, 12 mm.

Stimulus.	Color Seen.	Background.	45°	50°	55°	60°	65°	70°	75°	80°	85°	90°
Red	Red	Dark		3_b	4_b	3_b	3_b					
"	Orange[18]	"			1_b	1_b	2_b	3_b, 1	2_b	3_b	3_b	3_b
"	Yellow	"										
"	Red	"					1_b, I					
"	Orange	+ Hood	2_{gb}	2_{gb}, 1_b					1_b		1_b	1_b
"	Or.-Yel.[19]		1_{gb}		1_b, 1_{gb}	1, 2_b	1_b	1_b	1_b	2_b		2_b
"	Yellow				1_g, 2_b		1_b	1		1_b		
Orange	Orange	Dark	2_b	1_b		2_b, I	3_b	1_b	1_b		1_b	1_b
"	Or.-Yel.	"	2_b	2_b	5_b	1		1_b	1_b	1_b	2_b	
"	Yellow	"				3_b	2_b	3_b	1_b	4_b	2_b	2_b
"	Orange	"	1_b	1_b	1_b		1_b	1_b				
"	Or.-Yel.	+ Hood	1_{gb}	1_b		2_b	2_b	2_b	1_b			
"	Yellow		1_b	1_b	3_b	4_b	2_b	1_b	1_b			

B.

Observer F.

Stimulus.	Color Seen.	Size of Stim.	Background.	50°	55°	60°	65°	70°	75°	80°	85°	90°
Red	Red	12 mm.	Black	I	1_b	2_b	2_b	2_b	3_b	1, 1_b	1, 1_b	
"	Orange	"	"					1_b		2_b	1_b	2_b
"	Yellow	"	"									
"	Red	"	+ Hood	1								
"	Orange	"			1_b	2_b	1, 1_b	2_b, 1_v	1, 2_b	1	1	1_b
"	Yellow	"								1, 1_b	1, 1_b	1_b, 1
"	Red	5 mm.	Black	1		2_b	1_b	2_b	I, 1_b, 1	(I)I	II	II
"	Orange	"	"		1_b		1_b		1	1_b, 1(1)	1	
"	Yellow	"	"				1_b	1_b				
Orange	Orange	12 mm.	"			2_b	2_b	1	1_b	1_b		
"	Yel.-Or.	"	"			1_b	1_b	1_b	3_b		1_b, 1	1_v
"	Yellow	"	"							2		
"	Orange	"	+ Hood	1_b	1_b	1_b		1_v				
"	Yel.-Or.	"				2_b	2_b	1_v	1_b, 1	1_b	2	
"	Yellow	"					1_b		1	2	1	1_v, 1
"	Orange	5 mm.	Black					1_b	1_b			I_b
"	Yel.-Or.	"	"		1_b		2_b	1_b		1_v		
"	Yellow	"	"			2_b		1_b		3	1_b	

[18] The orange was described in every case as being as red as or redder than the orange disc.

[19] The orange yellow was almost pure yellow.

C.

Observer P.

Dark Background. Size of Stimulus, 12 mm.

Stimulus.	Color Seen.	60°	65°	70°	75°	80°	85°	90°
Yellow	Yellow					1_b	1_b	3_b, 1
Orange	Orange	1_b		1_b		1_b	2_b	1_b
"	Or.-Yel.							2_b
"	Yellow							2, 2_b
Red	Red					2_b	2_b	
"	Orange			1_b			2_b	1_b
"	Yellow							4

Orange yellow seen as yellow, 70°–85° inclusive.

4. *Conclusions to Section A.*

(*a*) *Effect of the Brightness of the Stimulus on its Color-tone.*

In peripheral vision the tone of the colors at the more refrangible end of the spectrum is decidedly dependent on the brightness of the stimulus. When the stimulus is sufficiently darkened, red, orange and yellow all tend to appear red in the more peripheral regions. The most pronounced results were obtained when the stimulus was darkened by contrast with a white background. In this case orange, and even yellow, appeared as pure, saturated red from the outer paracentral zone to the extreme periphery. Orange and yellow were seen as red, in this case, beyond the outer limits at which the red stimulus could be distinguished as red.

When the colors were relatively light, as was the case when they were observed on the black or gray backgrounds, the colors just mentioned appeared as yellow or yellow-orange at the periphery, or at the same points at which they appeared red with the light background. The most striking results were obtained when the color was brightened by contrast with a very dark ground.

Changes in brightness seem to have little effect on the colors at the less refrangible end of the spectrum. Purple becomes if anything slightly redder when darkened.

D.

Observer F.[20]

Stimulus.	Color Seen.	Size of Stimulus.	Back-ground.	25°	30°	35°	40°	45°	50°	55°	60°	65°	70°	75°	80°	85°	90°
Carmine	Carmine	5 mm.	Black				1_g	$1_g, 1$	3						I		
"	Violet	"	"							1							
"	Blue	"	"							2		2	2	2	2	(1)	1
"	Carmine	12 mm.	"							1	2	3	5	4			
"	Violet	"	"												4		
"	Blue	"	"										1	3			
"	Carmine	"	+	3								$1_g, 1_y$	$1_g, 1_y$	$3, I, 1_y$	$IV, 1_y$	I	
"	Violet	"	Hood											(1)		1	
"	Blue	"	"														
Violet	Violet	5 mm.	Black	3_g	$1_o, 1_g$		$1_y, 1_o$	1_g									
"	Blue	"	"		$3_g, 1_o$	$1_g, 1_o$	$1_g, 1_o$	$2_{g-o}, 1_g$	$1_o, 1$	1_y	1_o	1_o	$1_o 1$	1	2	2	2
"	Violet	12 mm.	"		$2_g, 1$	$1_g, 1_o$											
"	Blue	"	+Hood			2_{yg}	3_{gy}	3_{gy}	3_o	1_o	$2_y, 1_{o-g}$	1		1	$2_o, 1$		1
"	Violet	"	"					1_g	5_g	1_{g-o}	1_{yg}						
"	Blue	"	"						2	$1_{g-o}, 3_g, 1_o$	3_{y-o}	1_o					

[20] Suffix G-O means that F. was unable to tell whether the after-image was green or orange.

E.

OBSERVER R.

Size of Stimulus, 12 mm.

Stimulus.	Color Seen.	Background.	30°	35°	40°	45°	50°	55°	60°	65°	70°	75°	80°	85°	90°
Violet	Violet	White			3_{yg}	2_{yg}	3_{yg}	1_y, I	3_y, I	III, 1_y	III, 1_o	III	I		
"	Blue	"					2_{yg}			2_y	1			1_y	
Blue	"	"			1_{oy}, 1_{gy}^v	1_y	1_y		1_o, 3_y, 2	1_y^v, 2_y, 1_g, 1	1_y	1_y	1_y, 2	1_y, 2	I, 1
Violet	Violet	Grey			1_{yg}	1_y^b, 1_g^b	1_y^b, 1_{yg}, 1_y	1_{yg}	1_{yg}	$1_{y\text{-}g}$	$1_{b\text{-}g}$	1_{yg}	1		
"	Blue	"			2_y, 1	1_y, 1_o	3_y	4_y, 1_{yg}	2_y	1^v, 1_{yo}	1, 1_y^v	1, 1_g	1	1	
Blue	"	"							1_y, 1	1_o, 1	1	1	1		
Violet	Violet	Black			2_g^b		$2_{g\text{-}o}$, 2_y	$2^b_{o\text{-}g}$, 1_b	1_{yg}	1_{yg}^b					
"	Blue	"			2_g	$1_{g\text{-}o}$, 1	$1_{o\text{-}g}$, 1_y, 1_g	2_{og}, 1	$1_{y\text{-}g}$, 1	1_{gy}			2		
Blue	"	"					2	2_{go}, 1_y	$2_{o\text{-}g}$	1^v, 1_y	$1_{o\text{-}g}$	$1_{y\text{-}g}^v$	1_y^v	2	1, (1)

F.

OBSERVER R.

Size of Stimulus, 12 mm.

Stimulus.	Color Seen.	Background.	35°	40°	45°	50°	55°	60°	65°	70°	75°	80°	85°	90°
Carmine	Carmine	White		1_g		1	1, I	III, 1_y	I, I_{oy}	IV	II	I	II	
"	Violet	"				1_g		1_y, 1	1					
"	Carmine	Grey						1	1_{oy}, 1_{yg}, 1	3, 1_g	II, 1_g, 1	1, I		
"	Violet	"							1^r	1	4	2_o	1	
"	Blue	"										1_y, 1		
"	Carmine	Black					2_g	1_b	1_g		1, I	3_g	1^v, 1_g^v	2
"	Violet	"										1		1^b

(*b*) *Effect of Brightness on the Limits for the Color Fields.*

(*General Conclusions Continued from Page 55.*)

The limits for blue and violet are little affected by brightness changes. Yellow and carmine have the widest limits when the stimulus is very bright, as when it is observed on the dark background either with or without the black hood. The red component of orange is emphasized when the color is darkened by contrast with the white background, orange appearing, in this case, as pure red at the same points at which it appears yellow with the dark ground. The limits for red are practically the same with the light and the dark backgrounds (see p. 23), but the limits for orange and red are both decidedly decreased when these colors are brightened by contrast with the dark background covered by the black hood.

(*c*) *Effect of the Brightness of the Projection-ground on the Tone of the After-image.*

The after-image for blue and green-blue is yellow when projected on a white ground and red or orange when projected on a dark ground. When projected on a dark ground or observed in a darkened field, the after-image for blue is pure, saturated red at the extreme periphery. The after-image for violet, which is yellow with the light screen, appears, in most cases, greenish when projected on the dark screen. The after-image for red, orange and yellow is blue, regardless of the color-tone of the stimulus or of the brightness of the projection-ground.

The table gives the color-tone of the stimulus and of the after-image under various brightness conditions. When there is no specification concerning the brightness, the color is one which seems not to be affected by changes in brightness.

	Stimulus.	After-image.
Green blue, Blue	Seen as *blue*.	*Yellow* on light projection ground. *Red* on dark projection ground.
Red, Orange, Or. yellow, Yellow	Seen as *yellow* when relatively light. Seen as *red* or orange when relatively dark.	*Blue*.
Violet	Seen as *blue*.	*Yellow* with the light projection grounds. *Greenish* with the dark projection grounds.

Green is not followed by after-images at the more peripheral points. (The limits for the Hering green are much narrower than those for any other color.) A red after-image follows green at a greater degree of eccentricity with the dark than with the light projection ground. It should be kept in mind that the green of the Hering series is very unsatisfactory because unsaturated.

(*d*) *Effect of Changes in Brightness on the Relative Frequency and Saturation of the Peripheral After-image.*

Colored after-images follow color stimuli in a much larger percentage of cases in full than in decreased illumination. They also undergo a steady decrease in saturation as the brightness conditions under which they are observed are varied from maximum to minimum illumination. Only blue and yellow after-images were obtained, however, under the conditions which gave the largest total percentage of after-images and also, in general, the most saturated after-images (*i. e.,* when the after-image is observed on the white background in full illumination). Red after-images only occur when the projection-ground is dark or the general illumination is decreased (or under the conditions which give the smallest total percentage of after-images). These red after-images are, at least in the case of certain observers, fully as saturated as any peripheral after-images experienced under any brightness conditions. The very infrequent and poorly saturated green after-images experienced at the periphery require a darker projection-ground for their development.

At the upper brightness extreme (*i. e.,* when the stimulus and after-image are observed on a white background) characteristic after-images sometimes follow unperceived color stimuli.

(*e*) *Individual variation.*

Decided quantitative individual variations are shown throughout the results. These variations, however, seem to be due to the fact that the color-tone of stimuli and of after-images is more dependent on brightness conditions in the case of certain observers than in the case of others. The same general effect of brightness on color is apparent in all the results. For example, most of the observers saw the after-image for blue on the dark projection-ground, as pure red, but a few of them saw it simply as orange. The change due to the darken-

ing of the after-image is toward red in both cases, since the after-image for blue on the light projection-ground is always yellow. The results seem perfectly consistent throughout with respect to the individual variations. That is, if the results for a certain observer indicate a very marked effect of brightness in one experiment, they show a correspondingly decided effect in all the experiments with this same observer. For example, P obtained a red after-image for blue on the dark projection-ground and saw the orange-yellow stimulus as red when it was darkened by contrast with the white background. R got an orange after-image for blue on the dark projection-ground and saw orange-yellow simply as orange on the white background. P also saw red as red at a much greater degree of eccentricity than R with the dark background.

Section B. Observations Made with the Urfarben.

The work of the preceding section demonstrates clearly the necessity of maintaining constant conditions of illumination in a given series of tests, or at least of recognizing the effect of changes in the illumination not only on the brightness of the colors perceived (Purkinje phenomenon) but also on their color-tone. Consequently the work with the Urfarben has all been done on bright days when there was no variation in the illumination from day to day. It was found possible, by working with each observer at the same hour on different days, and by omitting the work on cloudy or dark days, to avoid any appreciable change in the general brightness conditions.

1. *Determination of the Urfarben.*

All four Urfarben were determined for observers F, Y and P. Owing to the time limitation only the Urroth could be determined for observer C.

Method.—The four colors were first found which did not change in tone as they were moved from the center to the periphery of the visual field. These colors were then mixed in pairs (*i. e.,* Urroth with Urgrün and Urblau with Urgelb), in such proportions that they canceled each other, giving gray. The proportion of each color thus determined was then mixed

with black and white until the brightness of the color matched that of a middle gray background, when the color fell upon a region of the periphery at which it appeared as colorless. Since it is an established fact that the brightness value of a color varies from the center to the periphery of the visual field, the peripheral method of equating brightnesses (*i. e.*, the method just described) seemed preferable to any other for our work, as we are here dealing with peripheral and not with central values.

The first part of the work, *i. e.*, through the determination of the Urfarben, was very carefully carried out, all the determinations being verified by repeated series of tests. The work on the limits for the Urfarben was somewhat hurried, as it came at the end of the academic year when the observers who had been serving for several months were leaving the University. A long stretch of dark weather made it impossible to work for days at a time in the spring and so brought the completion of the work well along into the summer (see footnote 25, p. 65).

The proportions of the various colors required for the Urfarben of the different observers are given in the following paragraphs.

Table XXV.

Gray Background. Determination of Urfarben

	Urgrün.	Urroth.	Urgelb.	Urblau.
Observer F.				
	Blue 49°	Blue 85°	Green 21.5°	Blue of series
	Green 311°	Red 275°	Yellow 338.5°	
Observer Y.				
	Urgrün.	Urroth.	Urgelb.	Urblau.
	Blue 49°	Blue 85.5°	Green 21.5°	
	Green 311°	Red 274.5°	Yellow 338.5°	Blue of series
			or	
			Y. green 40°	
			Yellow 320°	
Observer P.				
	Urgrün.	Urroth.	Urgelb.	Urblau.
	Green blue 90°	Blue 76°	Y. green 40°–48°	Blue of series
	Green 270°	Red 284°	Yellow 320°–312°	
Observer C.				
		Urroth.		
		Blue 75°		
		Red 285°		

2. *Equating of the Urfarben in Brightness and Saturation.*

The Urgrün and Urroth thus determined were found to be practically complementary in all three cases. That is, when mixed in the following proportions, they gave a medium gray which could be matched fairly closely by a mixture of black and white discs.[21]

TABLE XXVI.

Observer P.

158° Urroth composed of { 33° blue. 125° red.

202° Urgrün composed of { 50.5° green blue. 151.5° green.

Observers Y. and F.

210° Urgrün composed of { 181° green. 29° blue.

150° Urroth composed of { 35° blue. 115° red.

The proportions for the Urblau and Urgelb which gave a gray when mixed on the color-mixer, were as follows:

198.5° Urblau—composed of the blue of the series.
161.5° Urgelb—composed of 10° green + 151.5° yellow.

It was found possible to vary somewhat the proportions, given above for the Urblau and the Urgelb, without making the colors unstable, *i. e.,* without causing them to undergo a change in tone as they were moved from the periphery to the centre or *vice versa.* The possible variation was considerably greater for the Urblau and Urgelb than for the Urroth and Urgrün. The Urgelb determined for F and Y was stable also for P.

The four Urfarben, in the proportions just given, were equated in brightness with the same middle gray background. Thus we have the four Urfarben, in such proportions that they are equated with each other and with the middle gray background in brightness, and that each of the Urfarben is of equal saturation with its complementary Urfarbe.

[21] It will be seen that the proportions of the colors composing the Urfarben as given here are the same as in the original mixture. The gray produced by mixture of the Urroth and Urgrün was slightly reddish. The change in brightness necessary to equate the colors in brightness would change somewhat their saturation.

3. *Extent of Fields for the Urfarben.*

The limits of the colors thus equated in saturation and brightness were as follows (for table of limits see p. 64):

Table XXVII, A.

Observer Y.

Stationary Fixation.

Urroth.	*Urgrün.*
1. Black background.	
Seen surely at 60°.	60°.
Suggestion of color at 62.5°.	
2. Gray background.	
62.5°.	65°.
3. White background.	
Sure of red like Urroth at 61°.	Sure of Urgrün at 60°
Unsaturated red scarlet (*i. e.*, redder than Urroth) from 65° to 61°. If anything slightly redder than center at 61°.	
Urblau.[22]	*Urgelb.*
1. Black background.	
90°.	90°.
2. Gray background.	
85°.	85°.

B.

Observer F.

Stationary Fixation.

Urroth.	*Urgrün.*
1. Black background.	
52°.	50°.
2. Gray background.	
60°. (Color not well saturated until brought into 55°.)	55°. (Limits not absolutely sure until color brought into 47.5°.)
3. White background.	
At 50° seen clearly, but redder than Urroth—almost carmine.	Saturated red after-image at 55°. 50°.
Urgelb.	*Urblau.*
1. Black background.	
92.5°. Determinations were not made further out than 92.5°. The color was very well saturated out to this point.	87°. Very well saturated.
2. Gray background.	
90°.	90°.
3. White background.	

[22] No determinations were made between 85 and 90 degrees with the gray background. The colors were both clearly seen at 85° and not seen at 90°

The limits were not determined with the white background as the yellow which was Urgelb with the other backgrounds was orange with the white background.

Moving Fixation Point.

Gray Background.

Urroth at 57°.
Bluish from 80°–70°.
Reddish from 70°–60° .

Urgrün at 53°.
Bluish gray from 75° to 65°.

C.

OBSERVER P.

Stationary Fixation Point.

Urroth.	*Urgrün.*
1. Black background.	
Urroth at 49°.	51°.
2. Gray background.	
45°.	44°.
3. White background.	
55°.	50°.

Urgelb.	*Urblau.*
1. Black background.	
90°. (See once out of 4 tests at 92.5.)	92°.
2. Gray background.	
85°.	84°.
3. White background.	

The limits were not determined with the white background. The Urgelb appeared as orange at about 85°, grew more nearly yellow at about 55° and appeared practically pure yellow at the fovea.

TABLE XXVIII.

Limits for the Urfarben given in Degrees from the Fovea.

	Background.	Urgelb.	Urblau.	Urroth.	Urgrün.
	Black	92.5	87	52	50
O = F	Gray	90	90	60	55(?)
	White	—	—	50	50
O = P	Black	90	90	49	51
	Gray	85	84	45	44
	White			55 (redder than Urroth)	50
O = Y[23]	Black	90	90	60	60
	Gray	85	85	62.5	65
	White			61	60

[23] The limits for the Urroth and the Urblau were not determined for Y with the gray background at points between 85 and 90 degrees, so that it is possible that the color-limits may have been slightly wider than 85°.

4. *Conclusions to Section B.*[24]

(a) Effect of the Background on the Color-tone of the Urfarben.

The Urfarben determined with the middle-gray background were stable with the dark background in every case. With the light background the Urblau and Urgrün thus determined remained perfectly stable but the Urgelb and, to a lesser extent, the Urroth appeared slightly redder at the periphery than at the center; the Urgelb appearing decidedly orange and the Urroth slightly more scarlet as the stimulus is moved out to the periphery. If a larger proportion of green was added to the yellow, it appeared more nearly pure yellow at the periphery on the white background but greenish at the centre.

(b) Limits for the Urfarben.

α. Coincidence of the Fields for the Complementary Urfarben.[25]—With a given background, the limits for the Urgrün

[24] In this part of the investigation, the contrast between the various colors and the white or dark background was less than in our previous work, since the colors here were all matched to the middle gray background in brightness. Thus the yellow was darker than in the previous work and so presented less of a contrast with the dark ground and more of a contrast with the light ground, the blue on the other hand was lighter in the present case and so presented less of a contrast with the light background and more with the dark ground.

[25] It has been shown throughout our work that the results for a given stimulus vary slightly from day to day, even when the experimental conditions are kept as far as possible constant. Consequently, in most of our determinations a large number of tests was made at all points near the outer limits. The point was chosen as the outer limit, at which the stimulus was distinguished in a fairly large percentage of cases. In our work with the Urfarben lack of time made it impossible for us to determine the outer limits according to our previous method and consequently we considered the last point at which the color was ever seen as its limit.

Since the completion of the work reported in this monograph, a criticism of certain of our earlier investigations by Professor Titchener has raised the question concerning the significance of the the variability of results obtained near the outer color limits. Until further evidence can be obtained, we consider the problem as unsettled. We doubt whether absolutly invariable results can be obtained at the outer color limits under conditions of daylight illumination, and question the possibility of obtaining them under conditions of artificial illumination, especially in an investigation extending, as in the present case, over several months time. The results used by Professor Titchener and Mr. Pyle in the publication referred to, show irregularities similar to those to be found in our work. It is to be noted that, in this latter case, as well as in our work,

are practically coextensive with those for the Urroth, and the fields for the Urgelb with those for the Urblau. The greatest discrepancy occurs in F's results; with the dark background the limits for the Urgelb being slightly wider than those for the Urblau, and with the gray background the limits for the Urroth being wider than those for the Urgrün. In each of these cases the difference, which is only about 5°, is too small to be regarded as signifying any definite effect of the background on the stimulus color.

The limits for the Urblau and the Urgelb are in every case wider than those for the Urgrün and the Urroth. As already stated in the historical section (p. 6) we have no way of determining whether all four colors were equal in saturation.

β. Effect of the Brightness of the Background on the Color Limits and on Color Saturation.—The change of background seems to have no great effect on the limits for the Urfarben, though the Urgelb was perceived at the greatest degree of eccentricity with the dark ground and the Urgrün and Urroth at the greatest degree of eccentricity with the gray or light backgrounds. The colors were reported by all observers as much less saturated on the light than on the dark background. The Urroth and Urgrün appeared, if anything, more saturated on the middle gray than on the dark background, and the Urblau and Urgelb most saturated on the dark background.

The results obtained with the Urfarben before they had been equated in brightness and saturation indicate that the widest limits for the Urroth and Urgrün would be obtained on the middle gray background, and for the Urblau and Urgelb on the dark background. The limits were carefully determined only on the middle gray background.

In all our previous work, blue seemed to be more stable

the results with yellow and blue were much more regular than those with spectral red and green. In our work, the results with the Urroth and Urgrün showed as little variability as those with blue and yellow. For a more complete statement of the case see, *Jour. of Philos., Psychol. and Sci. Methods,* Vol. IV., 1909, pp. 398–403.

It is to be noted, moreover, that in so far as our results do not deal specifically with the determination of limits, but rather with the relative saturation of the stimuli and after-images and with the quality of the same, they are, in general, so pronounced as to be valid regardless of minor changes in illumination.

than red, yellow or green, and green more stable than the two remaining colors. The results with the Urfarben seem to show the same relative stability of these several colors, in that (1) the red and the green required the addition of blue before they became even approximately stable, and that the yellow which was the Urgelb with the dark or gray backgrounds was decidedly orange with the white background; and (2) the Urblau and the Urgrün were more stable than the Urroth and the Urgelb at the brightness extremes.

(*c*) *Individual Variation.*

It will be seen that the proportions of the different colors required for the Urfarben were very nearly the same for observers Y and F, and that the proportions for C, in so far as they were determined, were practically the same as those for observer P. Yet there was a decided difference between the results for P and C on the one hand, and those for Y and F on the other. That this difference is not due to any chance variation is shown by the fact that repeated determination of the Urfarben invariably gave the same proportions for the same observer. Moreover, repeated experiments with Y and P, showed that any slight change in the proportions of the Urroth and the Urgrün, as determined for each observer, caused the colors to appear as blue or yellow at the periphery. Y's Urroth, which required 10.5° more blue than P's (see p. 61) was distinctly bluish for P from 55° to 90°, while P's Urroth changed to yellow at the periphery (*i. e.,* at a point between 55° and 60°) for Y. These tests were repeated on different days and the same results obtained on each occasion.

It is interesting to note that the individual variations here are exactly in agreement with the general tendencies shown throughout the work. P and C reported the reds seen at the periphery as especially well saturated, and showed a somewhat greater tendency than other observers to see all red, orange and yellow stimuli as red. It seems quite natural that the observers for whom pure red and orange undergo the least change toward yellow at the periphery should require less blue for their Urroth than do those observers for whom these colors undergo a more decided change toward yellow.

III. GENERAL CONCLUSIONS AND THEORETICAL DISCUSSION.

A. General Formulation of Conclusions.

I. Red is experienced in the outer color zone (*i. e.,* the blue-yellow zone) under the following conditions: (1) When an orange or yellow stimulus is observed on a white background and so appears relatively dark by contrast with the background, and (2) when the after-image for blue is observed on a black projection ground or in a darkened room.

II. Any sufficient darkening of the red, orange or yellow peripheral stimuli causes them to appear either as colorless or reddish at the same points at which they appear yellow when relatively light, though the method just mentioned, namely, that of darkening the color by brightness contrast with the white background, gives more striking results than we have obtained by any other method of darkening the color.

III. The brightness of the projection-ground has a very decided effect on the color-tone of the peripheral after-image. The after-image for blue and green-blue is yellow when projected on a light background and red or orange when projected on the dark background. The after-image for violet is yellow when projected on the light ground, but shows a tendency to appear greenish on the dark ground. The after-image for orange or yellow is blue, regardless of the brightness of the projection-ground or of the color-tone of the primary sensation (see pp. 58–59).

IV. The relative frequency with which chromatic after-images follow peripheral color stimuli, as well as the saturation of the peripheral after-image, seems to be directly correlated with certain brightness conditions. After-images follow perceived color-stimuli almost without exception when the observations are made under conditions of brilliant illumination, or when the after-image is projected on a light screen in medium illumination. As the brightness of the projection-ground or of

the general illumination is decreased, after-images become relatively infrequent, and they are entirely lacking even for very intensive stimuli when the observations are made in an entirely darkened field. (Cf. experiments with black hood, p. 44.) As the illumination or the brightness of the background is decreased, the after-images grow steadily less saturated. On the white background, in brilliant illumination, the saturation of the peripheral after-image is equal to, or greater than, that of the stimulus, a relation which is gradually reversed as the illumination is decreased or the background darkened. The main exception to the above statement occurs in the case of the red after-image for blue and for green-blue. This after-image which is observed only under conditions of decreased brightness, is reported as the most saturated after-image obtained in peripheral vision and as very much more saturated than the stimulus which conditions it. The observers who obtained this red after-image were the ones who showed throughout the entire work the strongest tendency to see red at the periphery. The exception just mentioned does not hold for those observers who got an orange instead of a red after-image for blue on the dark background. In these cases the orange is described as clear and fairly well saturated but as distinctly less saturated than the stimulus. Our work suggests that brightness conditions could be obtained which would emphasize more decidedly the green after-image. The most favorable projection ground would probably be a grey somewhat lighter than that for the red after-image.

It is important to state here that there seems to be a degree of illumination at which the red after-image is described as at maximum saturation and that any decrease or increase of the illumination below or above this point results in a decided decrease in the saturation of the after-image in comparison with that of the stimulus color. That is, at a certain degree of illumination—a degree of illumination distinctly less intense than that of maximum saturation for other colored after-images—the red after-image appears as much more saturated than its stimulus color, but as the illumination is decreased the after-image gradually becomes less saturated than the stimulus-color. Consequently the relation between the brightness conditions and the relative satura-

tion of the after-image seems to hold for the red after-image as it does for other colors. But the illumination for maximum saturation is less in the case of these red after-images than in the case of any other peripheral after-image, a fact which is in perfect agreement with all our findings concerning the peculiarities of the peripheral sensitivity to red. The general correlation between achromatic adaptation and the peripheral after-image can be nicely illustrated by taking a series of tests with given stimuli in a room whose walls are black and then repeating the experiment with the same stimuli—and even with the same background—in a room whose walls are white, or by making the same series of tests on a white and then on a black background in a room of medium illumination.

IV. When the observations are made on a white background in brilliant illumination, after-images sometimes follow unperceived color-stimuli. The color-tone of these after-images is the same color-tone as that obtained for perceived color-stimuli under the given brightness conditions.

V. The Urfarben determined with the middle gray background were stable with the dark background. With the white background the Urblau and the Urgrün were perfectly stable, but the Urroth became slightly redder at the periphery than at the center, and the Urgelb grew decidedly more orange. The proportions required for the Urfarben differ slightly for different observers, but show no variation at different times for the same observer. The limits for each of the Urfarben were practically the same as those for its complementary Urfarbe. The limits do not seem to be appreciably affected by moderate changes in the brightness of the Urfarben (see footnote, p. 65).

VI. The individual variations shown throughout the work seem to be explained by the fact that certain observers have a greater peripheral sensitivity than others to red. The same observers who exhibited the greater sensitivity to red in the first part of the work, required less blue for their Urroth than the other observers.

B. Theoretical Discussion.

The theoretical discussion will be taken up under the following heads: (1) The sensing of red at the periphery; (2)

the effect of brightness on color-tone of the stimulus and the after-image; (3) the comparative sensitivity of the peripheral retina to red and to green; (4) the qualitative relation between the stimulus and the after-image (*i. e.,* are the stimulus and the after-image complementary to each other, in terms of either central or of peripheral vision?); (5) (*a*) the effect of brightness on the relative frequency and saturation of after-images; (*b*) the colored after-images of unperceived color-stimuli.

1. *The Sensing of Red at the Periphery.*

It has been suggested that the red perceived in the more peripheral regions is due to the 'tendency to interpret certain degrees of brightness in terms of certain color-tones.'[1] If this explanation is adopted it will be necessary to suppose that the blue and yellow perceived at the periphery are also due to brightness interpretation, since red is described by all observers as, if anything, more saturated than any of the other colors seen at the outer color limits. The following facts seem to prove that the color perceived is due to the color itself as well as to the brightness component of the stimulus: (1) gray, black and white failed to appear as colors or to be followed by colored after-images; (2) colors that are matched in brightness, as in the case of the Urfarben, are distinguished from each other; (3) the limits for a color are narrower when the color is decreased in saturation than when it is fully saturated.

A more satisfactory explanation seems to be that the red-sensing process, in a somewhat modified form, exists at the periphery as well as in the more central retinal zone. The main difference between the processes in the two cases seems to be that its activity at the periphery is more directly dependent on brightness conditions than at the center. This seems to follow from the fact that certain changes in color-tone which occur in central vision when the brightness is increased or decreased occur much more strikingly in peripheral vision with much less of a change in brightness. That is, the darkening of the colors at the more refrangible end of the spectrum causes

[1] H. Thompson and K. Gordon, 'A Study of After-images on the Peripheral Retina,' PSYCHOL. REV., Vol. XIV., 1907, p. 134.

them to shift toward red in central vision, but a variation in the brightness conditions which causes no appreciable change in central vision is sufficient to make orange and even yellow appear pure red in peripheral vision. This was shown by the tests in which the orange, which appeared red under certain brightness conditions in peripheral vision, was observed under the same conditions in central vision. In a few cases in central vision the color was reported as slightly redder than the orange of the Hering series, but was more often identified with it. In the same way a yellow which was decidedly red or orange at the periphery showed but the slightest golden tinge in central vision.

A question which naturally arises here is that concerning the complementary relations of peripheral stimuli. The issue is complicated by the fact that a decrease in saturation such that the color is still seen as color in central vision, causes the same stimulus to appear colorless in peripheral vision. The problem is one which requires further investigation in both central and peripheral vision.

2. *Effect of Brightness on the Color-tone of the Stimulus and of the After-image.*

If we admit that the red-sensing process exists at the periphery, but that its activity is more dependent on brightness conditions than in the more central zone, it will be necessary to explain how brightness can have such an effect on color. None of the theories which make brightness and color processes entirely independent of each other offers a satisfactory explanation of changes in color-tone when the only variation in the stimulus is an increase or decrease in its brightness.

The explanation of the Purkinje phenomenon which makes the changes in the relative brightnesses of colors due to the absorptive properties of the visual purple or rod-pigment (see historical section, pp. 12–13), does not explain equally well the changes in color-tone which accompany variations in brightness, both in peripheral and in central vision. This theory, as stated by Mrs. Ladd-Franklin, supposes that the rods are the organs for brightness vision alone. As the visual purple is

situated only in the rods, any increased effect of light of a particular wave-length, due to its absorption by the visual purple, will cause the stimulus to appear relatively darker or lighter, and possibly more or less saturated, but can in no way produce a change in color-tone.

It would seem quite possible for the Hering theory to make use of the explanation just given for the Purkinje phenomenon, by simply considering that the black-white substance alone exists in the rods while the two color substances, as well as the black-white substance, are to be found in the cones. If the color and brightness substances were arranged in this way, any absorption of colored light by the rod-pigment would intensify the effect of the color stimulus on the black-white substance and so increase the relative brightness of the color. But, even with this modification, the Hering theory seems to offer no explanation of *color* changes based on anything but a change in the wave-length of the stimulus.

At present we have only one hypothesis to suggest as a possible explanation for our results. This is that different intensities or brightnesses of stimulus are required for the excitation of the different color substances—*i. e.,* that a stimulus must possess a certain range of brightness, as well as a certain range of wave-lengths in order to be effective in arousing an activity in a certain color substances, and that the brightness required for the various color substances differs for the different colors at the long wave end of the spectrum. This brightness factor is effective to a very limited extent in central vision, to a much greater extent in peripheral vision. This would simply mean, that, as the color substance becomes more highly differentiated in central vision, it becomes less dependent on the brightness and more dependent on the wave-length of the stimulus. Consequently a stimulus of a given wave-length will condition an activity in a given color substance through a wider range of brightness and a narrower range of wave-lengths in central than in peripheral vision.

We seem able to explain our results most satisfactorily if we suppose that the yellow requires the greatest brightness of stimulus, and the red the least brightness of stimulus for its

excitation. The blues and greens occupy an intermediate position, requiring less brightness of stimulus than the yellow and more than the red. That such a dependence of color on the brightness of the stimulus exists seems to be shown by the fact that, in central vision,[2] yellow is the first color to disappear with decreasing intensity of stimulus and red the last, while blue and then green lose their color component at intensities between that for yellow and that for red.[3]

Another fact concerning central vision which seems to agree with our hypothesis, is that red is the first color to lose its color component as the intensity of the stimulus is increased above a certain point, so that red will appear as colorless at an intensity of stimulus at which the other colors are still distinguishable.

On the hypothesis just suggested the explanation of these changes in color-tone which accompany the Purkinje phenomenon in central vision, would be that the yellow, blue and green lose their color component at an intensity of stimulus at which red is still visible, because the color processes for the former three colors actually require a greater intensity of stimulus for their excitation than does the latter process. Orange loses its yellow component and appears pure red when its intensity is sufficiently decreased, because the intensity of the stimulus is not sufficient to condition activity in the yellow substance, but only in the red substance.

Since the color effects which accompany brightness changes in central vision were found to occur more strikingly in peripheral vision with a similar though much less extended change in brightness, we must suppose that the factor which is responsible for the change in central vision is more strongly operative in peripheral vision. If, as we have suggested, this factor is the brightness of the stimulus, the explanation for our results would be that a given color process at the periphery can be active only through a limited range of brightness. Yellow requires a greater brightness of stimulus for its excitation, while the red process is active only through the lower range of brightness

[2] This does not apply strictly to foveal vision.

[3] As already stated, Mrs. Ladd-Franklin offers a very different explanation for the fact that a relatively dark red is still seen as red, while a relatively light blue appears colorless. (Historical section, p. 12.)

values. The process for blue seems to be active under as wide a range of intensities in peripheral as in central vision, while the process for green seems to be incapable of activity under our brightness conditions or else to be entirely lacking in the other peripheral zone.

The term brightness is used in most instances in this discussion, instead of intensity in order that there may be no question concerning its application to all cases of change in the brightness of the color perceived, whether the change is produced by varying directly the intensity of the stimulus, or by superimposing the brightness on the color by contrast with a colorless background, or by projecting colored after-images on screens of different brightness values. In the discussion of central vision the term intensity is used because, in the investigations referred to, the brightness of the color has been modified by direct changes in the intensity of the stimuli. The hypothesis suggested is only partial and makes no attempt to give any final statement concerning the way in which the brightness component affects the color processes (see p. 79).

3. *The Comparative Sensitivity of the Peripheral Retina to Red and to Green.*

The question naturally arises as to the relative sensitivity of the peripheral retina to red and to green. Our results seem to indicate that, under certain conditions, red may be sensed at a greater degree of eccentricity than green. It is true that, with the exception of the Urroth and the Urgrün, the red and the green used throughout the investigation were not equated in saturation, and that the greens are unquestionably less saturated than the reds. It is also true that the results with the Urfarben give practically the same limits for the Urroth and the Urgrün, but these colors were a bluish red and a bluish green. There seems to be no way of equating a spectral red and a spectral green, or their pigment representatives, in saturation, if the only validity of such a comparison equation rests on the cancellation of one color by another, since the two colors are not complementary and so cannot be made to cancel. The stimulus which was seen as red at the greatest degree of eccentricity was a

yellowish red (*i. e.*, orange) and its complementary color is a very bluish green, which is seen as pure blue at the periphery. Perhaps the only statement that we are justified in making is that none of the stimuli used in our investigation, including yellow-green, green, and blue-green, were seen as green at as great a degree of eccentricity as that at which certain stimuli were seen as red, and that the sensitivity to red seems to be more strongly influenced by brightness conditions than is the sensitivity to green.

This greater dependence of the red sensitivity on brightness is also suggested by the fact that the yellow-green, green and blue-green do not show as great an effect of change in brightness as do those exhibited by the yellow, orange-yellow, orange and red stimuli. That is, if we compare the results obtained with the yellow-green, green or blue-green on the white background, with those for the same stimuli on the dark background, we find very little difference in the two sets of results except that green is seen as yellow less frequently with the light than with the dark background, while the results for red, orange, yellow, and to a lesser extent for carmine, stimuli with the dark background are very different from those obtained with the light background, both in the tone of the colors perceived and in the limits for the various colors. Moreover, the after-image for both green-blue and blue comes out as red, when it is observed on the dark background and as yellow when it is observed on the light background; while the after-image for red, carmine and violet, although it tends to appear as green at a somewhat greater degree of eccentricity with the dark than with the light background is relatively infrequent with the dark background, and when seen is very poorly saturated. As already suggested, the green after-image would undoubtedly be more emphasized by a projection-ground of just the right brightness value, but further experiments indicate that the green after-image would not be obtained at as great a degree of eccentricity as the red, nor show as marked changes in color-tone with variations in the brightness conditions.

Although our results seem to suggest, under certain conditions, a more widely extended sensitivity to red than to green,

the only conclusion actually justified by our results is that the green sensitivity is not as dependent as the red on brightness conditions.

It seems difficult to explain, on the basis of any theory which makes the red and the green processes reversible, why the peripheral sensitivity to red and to green should not present exactly analogous cases. The difference, as already stated, seems to be that the red sensitivity is more dependent on brightness conditions than is the green sensitivity. The results seem to agree with our hypothesis, that in peripheral vision a stimulus must possess a certain brightness to arouse an activity in the yellow substance and that a stimulus of less brightness will arouse an activity in some other color substance or merely in the brightness substance, since at the same degree of eccentricity, a light green is seen as yellow while a dark green tends to appear merely colorless.

4. *The Qualitative Relation Between the Stimulus and the After-image.*

The question, raised by certain investigators, concerning the relation between the peripheral stimulus and its after-image (*i. e.,* whether the after-image is complementary to the primary sensation at the point stimulated) seems to depend for its answer on the brightness conditions under which the observation is made. Under certain conditions the after-image is complementary to the primary sensation at the point stimulated: An orange, for example, observed on a dark or gray ground, appears yellow but is followed by a blue after-image regardless of the brightness of the projection-ground. Under other conditions the after-image may be complementary to the stimulus as seen in central vision, though illustrations of this are somewhat infrequent: For example, a green-blue which is seen as blue may be followed by an orange after-image when the after-image is projected on a dark ground. Finally, the after-image may not be complementary to either the peripheral or the central sensation: For example, an orange stimulus, observed on a white background, appears red and is followed by a blue after-image regardless of the brightness of the projection-

ground; or a blue is followed by a red after-image when the after-image is projected on a dark ground. The following list shows the relation between the after-image and stimulus.

I. Cases in which the After-image is Complementary to the Primary Sensation at the Point Stimulated.

Stimulus.	After-image.
Blue, seen as *blue* under all brightness conditions.	*Yellow,* when projected on light ground
Red, *Orange*, *Yellow* } Seen as *yellow* when relatively bright.	*Blue,* regardless of brightness of projection ground.

II. Cases in which the After-image is Complementary to the Stimulus as Seen in Central Vision.[4]

Stimulus.	After-image.
Green-blue, seen as blue.	*Orange,* when projected on dark ground.
Green, seen as yellow.	*Red,* when projected on dark ground.
Violet, seen as blue.	*Yellowish green* when projected on the dark ground.

III. Cases in which the After-image is not Complementary to the Stimulus as Seen either in Central or Peripheral Vision.

Stimulus.	After-image.
Blue, seen as blue.	*Red,* when projected on dark ground.
Red, *Orange*, *Yellow* } Seen as red when relatively dark.	*Blue,* regardless of brightness of projection ground.

Two views have been held concerning the relation of the after-image to the peripheral stimulus. These, as reported by Baird,[5] are as follows: "Both these investigators (Aubert[6] and Franz[7]) report that the peripheral after-image is of the same color as the central—that, *e. g.,* the after-image of a purple stimulus is green, no matter at what part of the retina the after-image be aroused. That this statement is erroneous, we have succeeded in demonstrating by means of an experiment in which an intensive purple stimulus and a long exposure were employed.

[4] Stimuli which appear the same in peripheral and in central vision are omitted here (cf. blue and yellow).

[5] Baird, *op. cit.,* pp. 64–65. The following references (*i. e.,* footnotes 6–9, inclusive) are from Baird's text.

[6] Aubert, H., 'Ueber das Verhalten der Nachbilder auf den peripherischen Theilen der Netzhaut,' *Moleschott's Untersuchungen,* IV., 1858, S. 220ff.

[7] S. I. Franz, 'After-images,' Psychol. Review, Mon. Supp., III., 1899, p. 29.

We found that the application of this stimulus to different regions of the retina gave the following after-images: Green at 0°, blue-green at 25°, bluish at 40°, and dark gray (?) at 50°. The results of this experiment are fully in accord with the findings of Adamük and Woinow,[8] who also report that the color of the after-images aroused at any retinal region is complementary to the color of the primary sensation produced at that region. Our results are further confirmed by the data contained in a more recent paper by Walther."[9]

In work under our experimental conditions it is evident that the peripheral after-image may be 'of the same color as the central,' or it may be of the color complementary to the primary sensation produced at that region, or it may fail to bear either of these relations to the stimulus, depending on the achromatic conditions under which the observations are made.

Any explanation of the effect of brightness on color phenomena would necessarily show exactly how the brightness of the stimulus effects the color processes. If the color and brightness are conditioned by activities in separate retinal substances, there seem to be two possible ways of explaining the facts: Either the brightness of the stimulus has a direct inhibitory or stimulating effect on the color processes, or the brightness primarily effects the brightness substance and the activity in the brightness substance has some differential effect on the color substance. With our present knowledge of retinal processes, it seems impossible to decide which of the above hypotheses is more probable. The fact that our most striking effects were obtained when the brightness is superimposed on the color, *i. e.*, when the brightness is largely determined by contrast with a brightness background, or when the after-image is projected on a light or dark ground, seems at least to justify the statement that the superimposed brightness acts in such a way as to inhibit, increase or modify the color activity.

[8] Adamük and Woinow, 'Beiträge zur Theorie der negativen Nachbilder,' *Graefe's Archiv.*, XVII., 1, 1871, S. 141f.

[9] Anthon Walther, 'Beobachtungen über den Verlauf centraler und extramacularer Nachbilder,' *Pflüger's Archiv.*, LXXVII., 1 and 2, 1899, S. 53–69.

5. (*a*) *Effect of Brightness Conditions on the Relative Frequency and Saturation of the Peripheral After-image.*

In addition to the very marked effect which the brightness conditions have on the color-tone of the after-image, is their equally important effect on the relative frequency and saturation of the after-image. As has been abundantly indicated,[10] all our work has gone to show that a very definite correlation exists between local and general brightness conditions and the relative frequency with which after-images are observed, as well as the relative saturation of such after-images as are observed.

Baird has already reported the complete absence of peripheral after-images under conditions of complete dark adaptation. Our results in a completely darkened field agree with Baird's in showing a practical absence of after-images under these conditions.

Misses Thompson and Gordon[11] have suggested that the reason for this difference between light and dark adapted vision, is that white light is actually necessary for the production of the after-image on the peripheral parts of the retina. They suggest an explanation in terms of the Ladd-Franklin theory, which is in brief, that when the color molecule has been partly decomposed by a given color-stimulus, the residual portion of the molecule requires the added excitation of white light for its decomposition. This would mean that white light has some effect on the color substance, if only in the sense that it adds to the excitability of the color substance.

According to the Müller and Hering theories there seems to be no way of explaining the absolute dependence of the after-image on the general illumination, since the antagonistic or reverse process to that excited by the stimulus, would be set up in the brightness as well as in the color substance, and so condition a light or dark after-image, according to the brightness of the original stimulus. It would seem, then, that the Müller and Hering theories serve to explain the appearance of the central after-image, but not the absence of the peripheral after-image in dark-adaptation.

[10] Cf. pp. 59ff., 68ff.
[11] *Cit.*, 133–134.

(b) The Colored After-images of Unperceived Color Stimuli.

As in our previous work after-images were sometimes perceived when the stimulus color was not distinguished. Under our experimental conditions, these after-images occurred almost exclusively with the white background in brilliant illumination. By brilliant illumination is meant the sort of light obtained from a skylight, or as in the present case, from our large north window, on a very bright, clear day in a room with white or light gray walls. The results seem so directly dependent on the illumination that it is necessary to work during the middle part of even a bright day. These after-images seem to be merely another illustration of the correlation between the illumination and the saturation and frequency of the after-image (see preceding section). They seem to represent typical results of one extreme of brightness adaptation, of which the other extreme is complete dark adaptation with its practical absence of after-images.

These after-images occur when the local brightness conditions are such as to favor the color of the after-image more than that of the stimulus. For example, with the white background and projection-ground, an unperceived yellow is sometimes followed by a clear, decided blue after-image, while under the same conditions an unperceived blue may give rise to a clear yellow after-image. In both of the cases just mentioned the stimulus is relatively dark because of brightness contrast with the white background, while the after-image is relatively light because projected on the white ground. It will be remembered that the limits for yellow are narrowest when the color is darkened by contrast with a white background and widest when the color appears light because of contrast with a dark background. Blue, for most observers, shows a similar though very much less marked effect of decrease in intensity (*i. e.,* its limits are narrowest when the color is darkened by contrast with a light background). When the blue stimulus is given on the white background, it is very dark and so not seen at as great a degree of eccentricity as under other conditions, while the yellow after-image which is light because projected on the white ground, comes out under just the conditions which most

favor the perception of yellow. When, on the other hand, the yellow stimulus is given on the white background it fails to be seen at points at which it would be clearly seen with the darker backgrounds, but the after-image, projected on the white screen, is blue, or a color affected much less than yellow by changes in brightness. The same general explanation would hold for red and orange, since these stimuli appear colorless with the white background at the same points at which they appear yellow with the dark backgrounds.

In several instances, in our later work, a red after-image has followed an unperceived green when the stimulus was given on the white background and the dark screen pushed over the color, and a green after-image was obtained for red and orange when the projection-screen was middle grey or black.

The two conditions mentioned as necessary for the after-image, can perhaps be correlated as follows: The white background drowns out the stimulus color by darkening it beyond the point at which it can be seen as color. The brighter the illumination the greater the contrast, consequently the color limits are narrowest when the illumination on the white background is greatest. Now if the after-image is projected on a screen which favors the after-image, the result is the perception of the after-image even though the stimulus color is not seen. Undoubtedly a larger percentage of after-images would be obtained for unperceived stimuli, if the projection-screens were simply determined so as to most emphasize the after-image color, and the background to least favor the stimulus color.

The failure of after-images to appear in dark adaptation seems to be analogous to the effect produced on any color by mixing it with black. That is, when a peripheral stimulus or after-image is darkened beyond a certain point it loses its color component and appears merely as brightness. This occurs when the brightness of the color is such that the color is still clearly perceived in central vision. As certain colors are changed from maximum to minimum brightness a series of color changes occurs. Particular brightness values emphasize particular colors in the case of either the stimulus or the after-image. At the upper brightness extreme, *i. e.,* when the stimulus is suffi-

ciently brightened by contrast with the dark background, or the after-image is projected on the white background, only blue and yellow are perceived at the outer color zone. As the brightness is decreased all stimuli tend to appear greenish or red instead of yellow (blue and violet are, of course, exceptions). Finally, however, a point is reached at which neither stimulus nor after-image can be recognized, and this, for the after-image, is complete dark-adaptation. With the stimulus we approached this condition when the color was darkened by contrast with a brilliantly illuminated white background.

As already stated, the facts seem to agree with those already established concerning central vision, but to show a greater dependence of the peripheral than of the central color-sensitivity on brightness conditions. The one exception to the above statement seems to be the dependence of the peripheral after-image on brightness conditions. This latter fact seems quite in agreement with the general character of peripheral results but not with the facts of central vision.

It may be that further work in central vision will show that the two cases are perfectly analogous. Certainly it is quite possible that, if central after-images are investigated under sufficiently varied conditions of achromatic adaptation, they will be found to be affected in the same general way as peripheral after-images by these conditions.

The theoretical conclusions are necessarily incomplete and purely hypothetical. As already stated, our knowledge of retinal processes is so incomplete as to render speculation of little value. Moreover, several questions raised in this investigation or suggested by it, must be settled by further experimental evidence before we can complete even the few theoretical suggestions made here. The work as it stands will at least answer several of the questions concerning the quantitative and qualitative relations of peripheral stimuli and after-images and show the dependence of both on achromatic conditions. The following statement, recently made by Baird,[12] is shown to hold only under certain achromatic conditions: "Even in light adaptation they (*i. e.*, peripheral after-images) are less per-

[12] E. B. Titchener and W. H. Pyle. 'On the After-images of Subliminally Colored Stimuli.' *Proc. of Amer. Philos. Soc.*, Vol. XLVII., No. 189, 1908, p. 377.

ceptible than are the primary images aroused by the given stimulus," whereas an hypothesis like that suggested by Franz[13] seems utterly untenable. His statement is as follows: "This gradual, but finally absolute, lack of ability to distinguish an after-image is probably due to several factors. Aubert mentions that the periphery is more easily fatigued than the fovea; but he does not seem to consider that this may be partly mental and not entirely physiological. From observations made during the progress of the experiments it seems likely that the inability to attend to these things not in its immediate vicinity is the primary reason for the lack of images toward the periphery, and for the long durations at the fovea."

We are confident that all the phenomena described in the present monograph, including the "colored after-images of unperceived color stimuli" have some direct physiological explanation, though further work must determine the exact nature of the explanation.

[13] Franz, S. I. *Psychol. Rev., Monograph Supplement,* Vol. III., 1899–1901, p. 30. Franz worked for the most part under conditions of dark-adaptation.

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[1] This bibliography is simply intended to supplement that given by Baird (*op. cit.*, 74–80). Our list includes the more recent articles which have come to our notice, as well as those prior to the year 1905 which have special reference to achromatic adaptation or are not included in Baird's bibliography.

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